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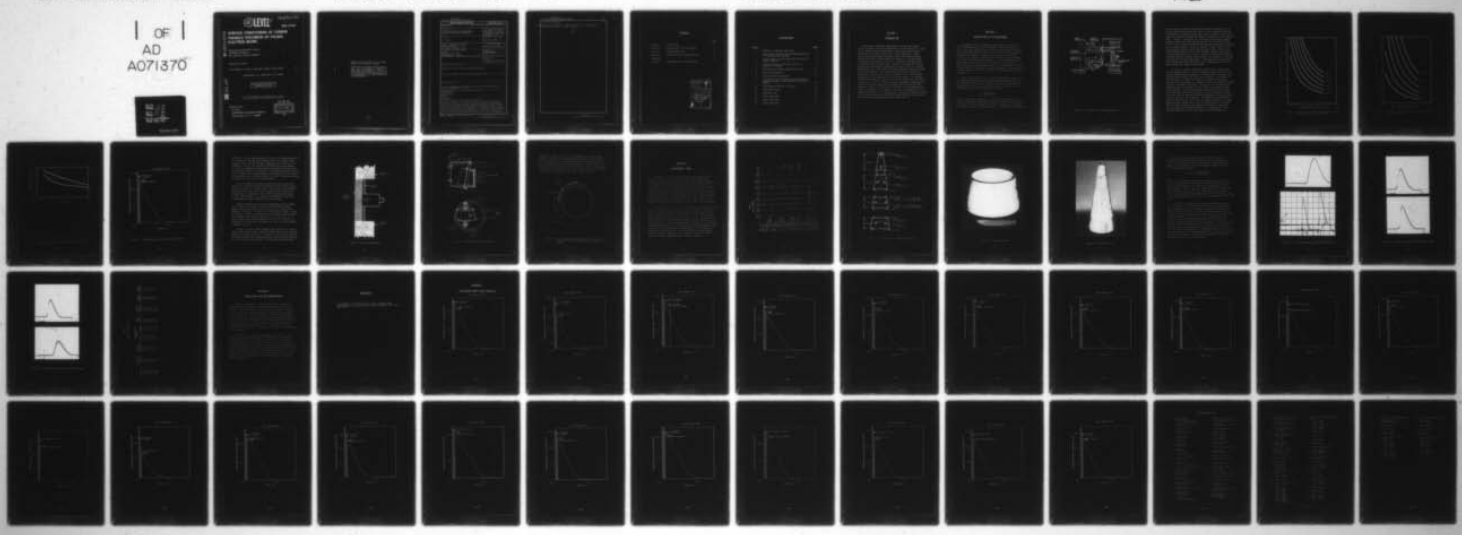

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SURFACE CONDITIONING OF CARBON PHENOLIC SPECIMENS BY PULSED ELECTRON BEAMS

Physics International Company
2700 Merced Street
San Leandro, California 94577

September 1978

Final Report for Period 22 May 1978—1 June 1978

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The OWL II generator, in conjunction with the large area beam hardware, generated a reproducible uniform electron beam capable of removing between 0.013 and 0.025 cm depth of phenolic from carbon phenolic ablator surfaces. The beam had a diameter of 19 cm (280 cm^2). Specimens of staple rayon and continuous filament rayon carbon phenolic were irradiated. Samples included both flat and conical section configurations. Stress pulse measurements were performed on each type of material using quartz gages. The irradiated

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specimens were forwarded to Science Applications Inc., and Prototype Development Associates for further testing.

CONTENTS

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ILLUSTRATIONS

SECTION 1

INTRODUCTION

This report describes experimental work performed under contract DNA 001-77-C-0193 between May 22, 1978, and June 1, 1978, on the Defense Nuclear Agency OWL II large-area beam facility. The objective of this effort was to obtain samples of staple rayon (SR) and continuous filament rayon (CFR) carbon phenolic ablator materials with the phenolic removed to a uniform depth of between 0.013 cm and 0.025 cm by irradiating specimens with a large-area pulsed electron beam. Both flat and conical section samples were successfully irradiated and then sent on to Science Applications Inc. (SAI) and Prototype Development Associates (PDA) for further testing. On selected SR and CFR flat samples the stress-time histories at the rear surfaces of the 1.27-cm-thick specimens were monitored with 1.1-μs quartz gages. The average diode mean voltage for this test series was 320 kV with an average fluence of 17 cal/cm^2. After filtering and magnetic compression the electron beam at the target location had an effective mean energy of 270 kV, a fluence of 10 cal/cm^2, and an estimated mean angle of incidence of 57 degrees. The area of irradiation at the target was 280 cm^2. This constitutes a 50 percent increase in beam area for these phenolic removal conditions over what was achieved in the previous experimental series (Reference 1).

SECTION 2

DESCRIPTION OF THE EXPERIMENT

A schematic of the large-area beam system with axial magnetic transport used in this experiment is shown in Figure 1. This is the same hardware as was used in the experiment reported previously under this contract. Prior to this testing, however, an analytical parameter study was carried out for the OWL II machine in an effort to maximize the available beam area within the context of the existent hardware. This was deemed necessary since some of the conical section samples (frusta) would fit within the area of the previous beam with little margin for error. By maximizing the beam area the sample alignment constraints were relaxed, allowing faster shot-to-shot turn-around times during the experiment.

With an experiment of this type the two prime variables are the pulse charge voltage and the anode-cathode separation. The pulse charge voltage is the voltage at which the main switch in the generator closes. The diode voltage V_D is related to the pulse charge, V_{pc}, by the following equation:

$$V_D = \frac{0.68\ V_{pc}\ Z_L}{1.9 + Z_L}$$

and Z_L is the diode impedance. Figure 2 illustrates the calculated relationship between pulse charge and anode cathode spacing for a range of diode voltages. The OWL II generator is designed to deliver a 1-MeV, 0.55-kA pulse into a 1.9-ohm diode matched load.

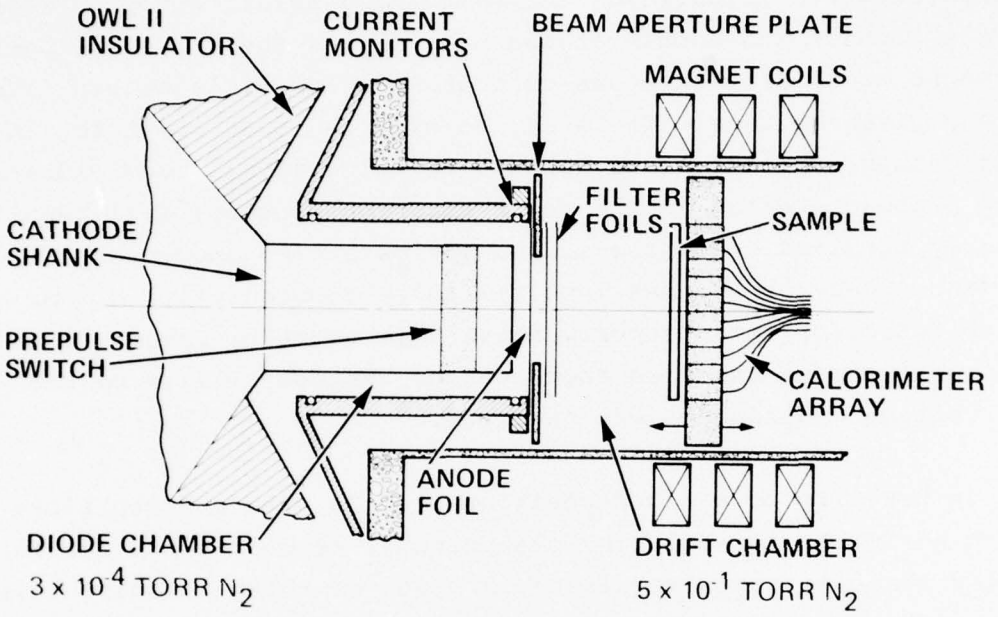


Figure 1 Schematic of ablator equipment.

At this voltage, however, the phenolic would be removed to a far greater depth than desired; the object of the parameter study was to determine the lowest voltage that could be achieved while still obtaining sufficient fluence to remove the phenolic to the required depth. Figure 3 illustrates the calculated relationship between average fluence and anode-cathode spacing for the 410-cm^2 diode. As can be seen, smaller anode-cathode spacings yield higher fluences for any given voltage. There is, however, a lower limit for the anode cathode spacing since below a certain value, diode closure (from plasmas created in the field emission process) will result in early termination of the pulse. Below a 6-mm anode-cathode gap the diode behavior becomes less reliable; consequently, a 7-mm gap was selected for these experiments. This geometry yielded stable diode performance and good shot-to-shot reproducibility of both mean voltage and fluence was obtained.

In order to obtain a deposition profile with a steep slope (which maximizes control over the phenolic removal depth for the shallow removal depths required), a 0.005-cm-thick titanium filter was positioned between the diode and the sample. The effect of this filter is to reduce the kinetic energy of the electrons, increase their mean angle of incidence, and reduce the beam fluence. Figure 4 illustrates the effect of the filter on the energy and estimated angle of incidence of the beam as a function of mean diode voltage. For the average shot conditions for this series, the 320-kV diode voltage is reduced by 50 kV in passing through the filter and the emerging e-beam is estimated to have an average angle of incidence of 57 degrees. An example of the deposition profile from a typical shot, 4375, is shown in Figure 5. On this pulse the mean voltage was 316 kV, the fluence was 17.6 cal/cm^2, and the depth of removal was measured at 0.015 cm. The first part of the profile (shaded portion) is the deposition in the titanium anode and filter, which have a total thickness of

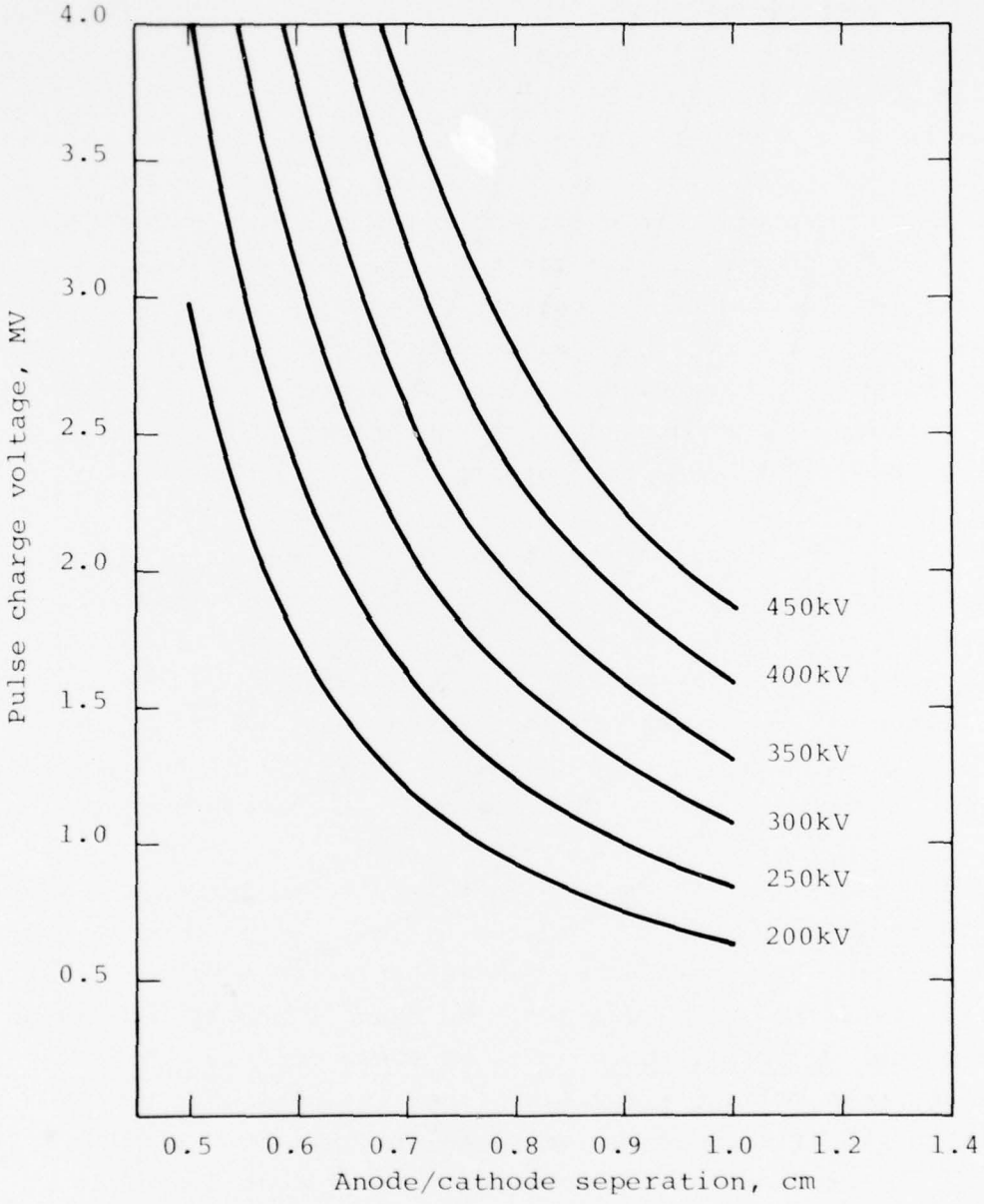


Figure 2 Pulse charge voltage versus anode/cathode gap for various diode voltages.

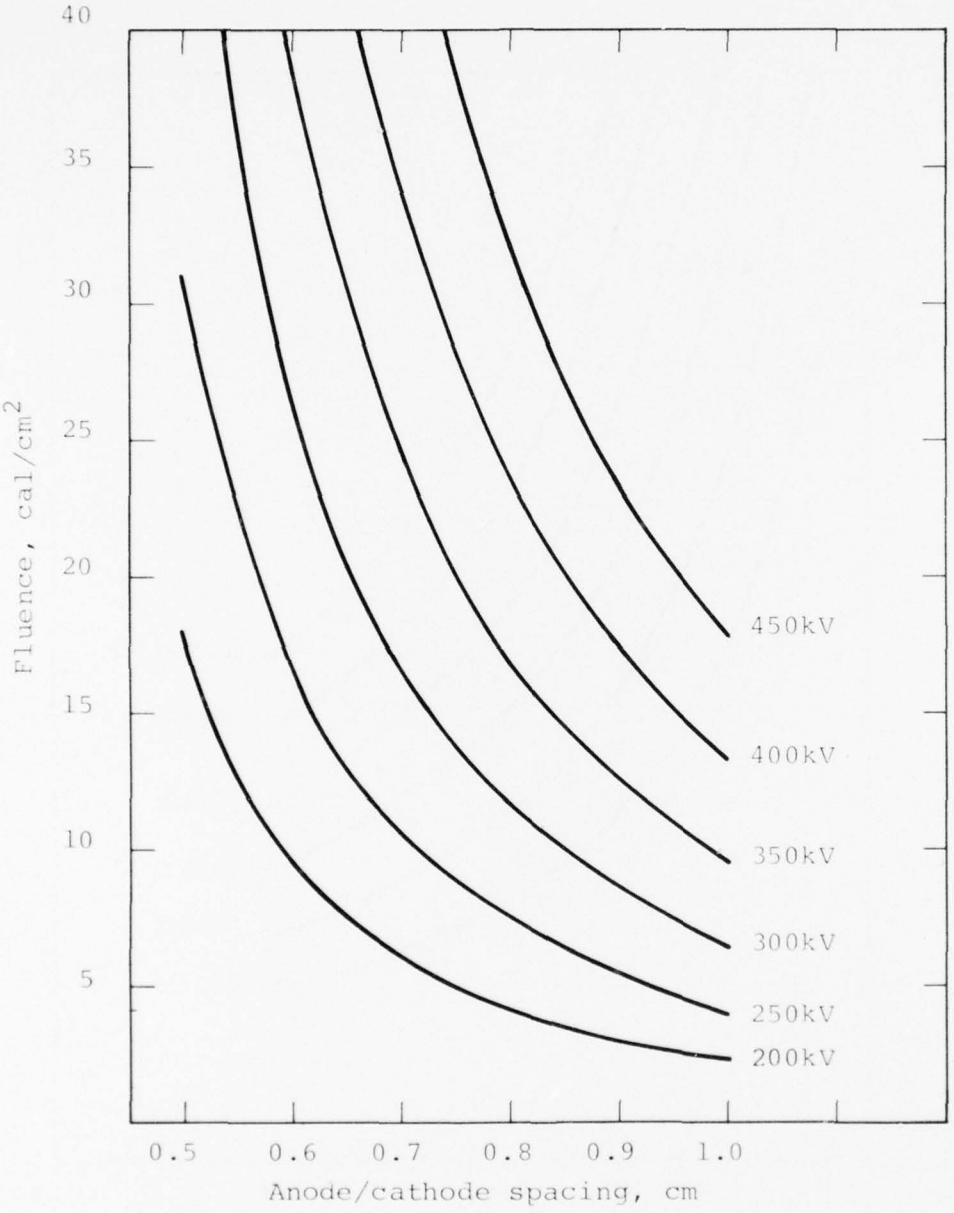


Figure 3 Fluence versus anode/cathode gap for 410-cm^2 diode on OWL II.

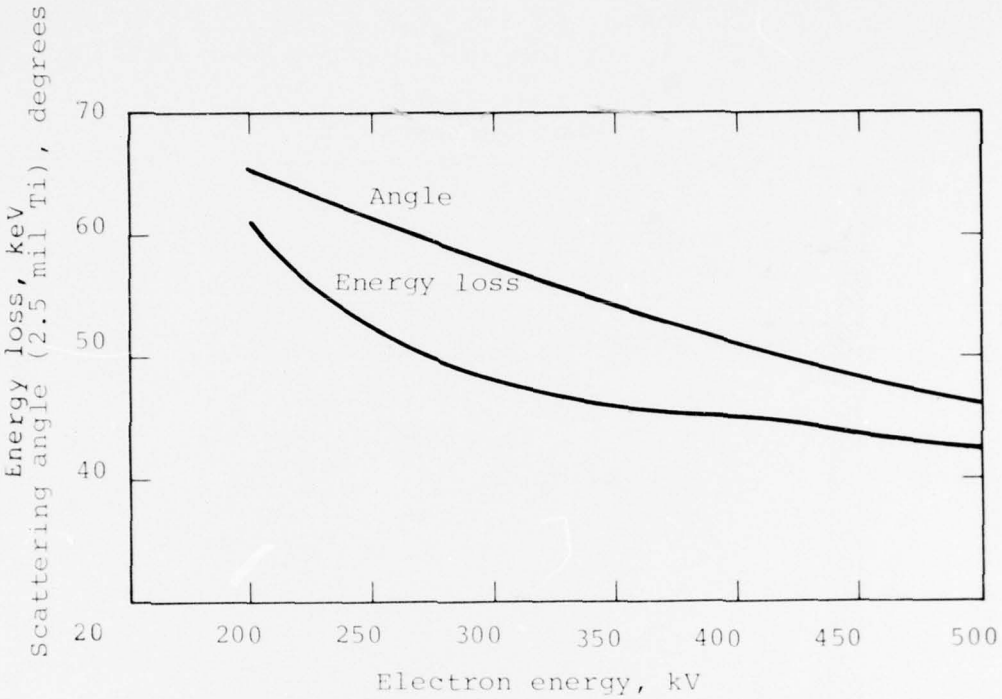


Figure 4 Effect of filter on electron beam as a function of voltage.

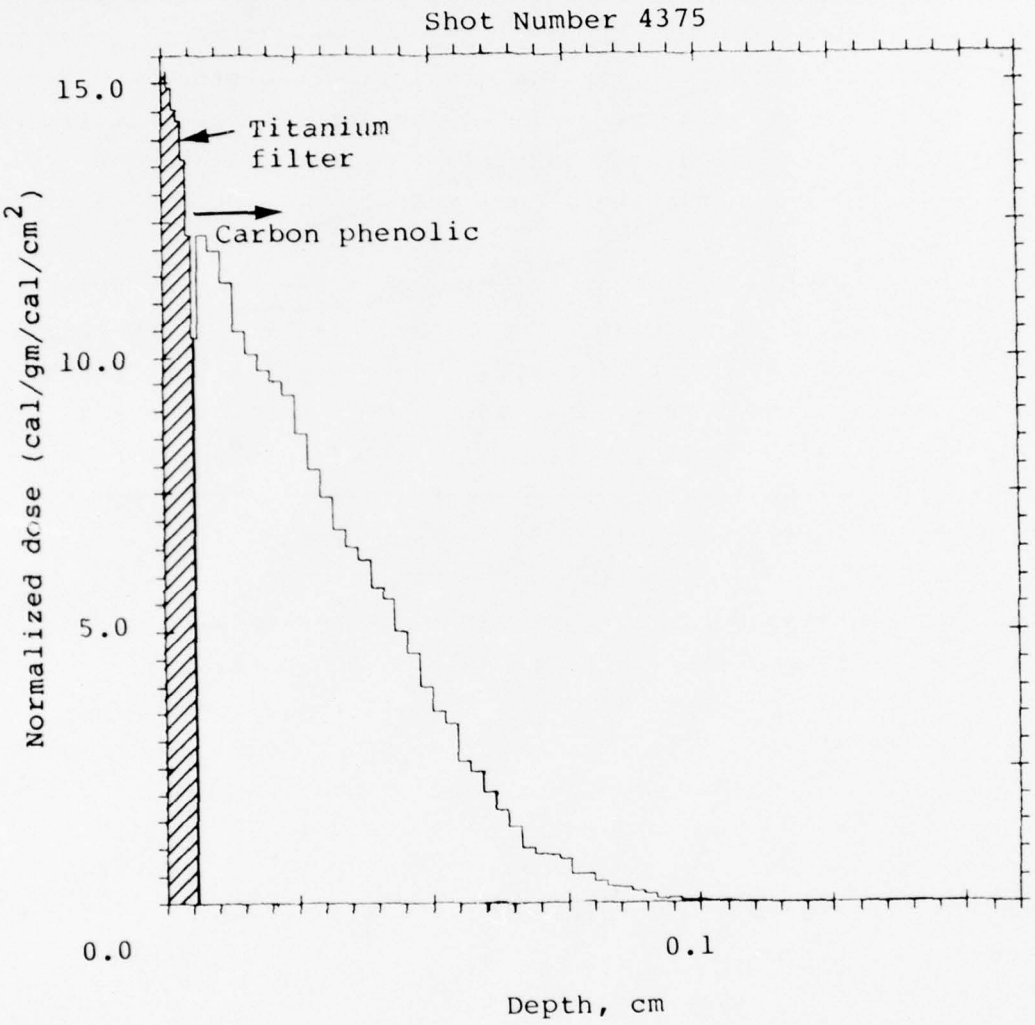


Figure 5 Representative energy deposition profile.

0.0064 cm. At the removal depth of 0.015 cm the normalized dose is 9.5 cal/gm per cal/cm^2, which combined with the measured diode fluence of 17.6 cal/cm^2 and beam compression by a factor of 1.2 indicates a dose of 201 cal/gm at the depth within the sample. This value corresponds to the generally accepted threshold value for phenolic removal of 200 cal/gm. Calculated depth dose profiles for all sample shots are presented in the appendix of this report. These profiles are calculated directly from the voltage and current waveforms obtained on the individual shots.

All flat samples irradiated during this test series were mounted in a graphite mask and backed with 0.635-cm-thick plexiglass to prevent rear surface spall. The original experimental plan was to have the flat samples unbacked unless severe rear surface spall was observed. Pulse 4372 showed a great amount of rear surface spall; all subsequent flat samples, therefore, had plexiglass backers coupled with vacuum grease.

Samples intended for stress-time measurements were lapped flat on their rear surface before bonding the quartz gages. Backers for these samples had a hole cut in the center to accommodate the gages. A schematic of the mounting scheme is shown in Figure 6. Furane 202 epoxy was used to bond the quartz gages to the samples with bond thickness of $\leq 1.2 \times 10^{-3}$ cm. All quartz gages had an outside diameter of 3.175 cm, a guard ring diameter of 1.270 cm and a thickness of 0.635 cm, which provides a readtime of 1.1 μs.

Frusta or conical section samples were mounted on a special fixture fabricated by PDA. Front and side views of this mounting hardware are shown in Figure 7. Because of the relative sizes of the frusta and the beam irradiation area, two shots were required to fully irradiate each section. The unirradiated portion was

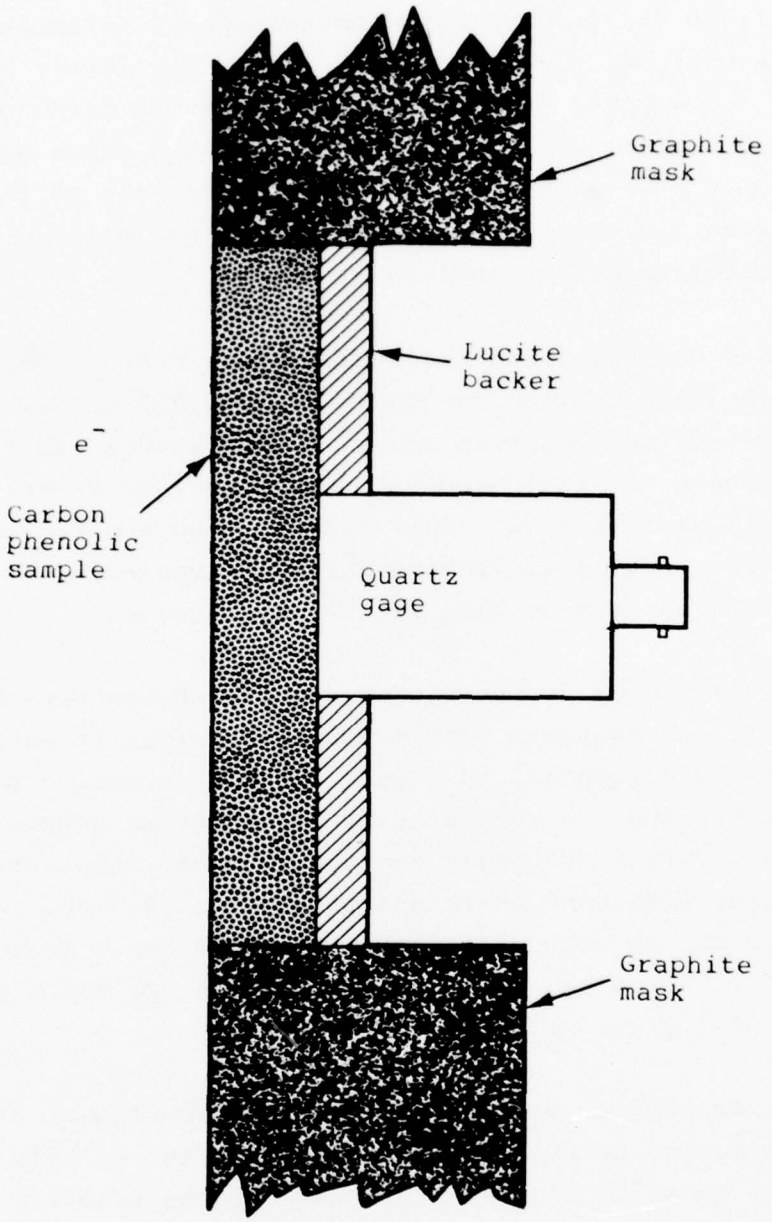


Figure 6 Quartz gage geometry.

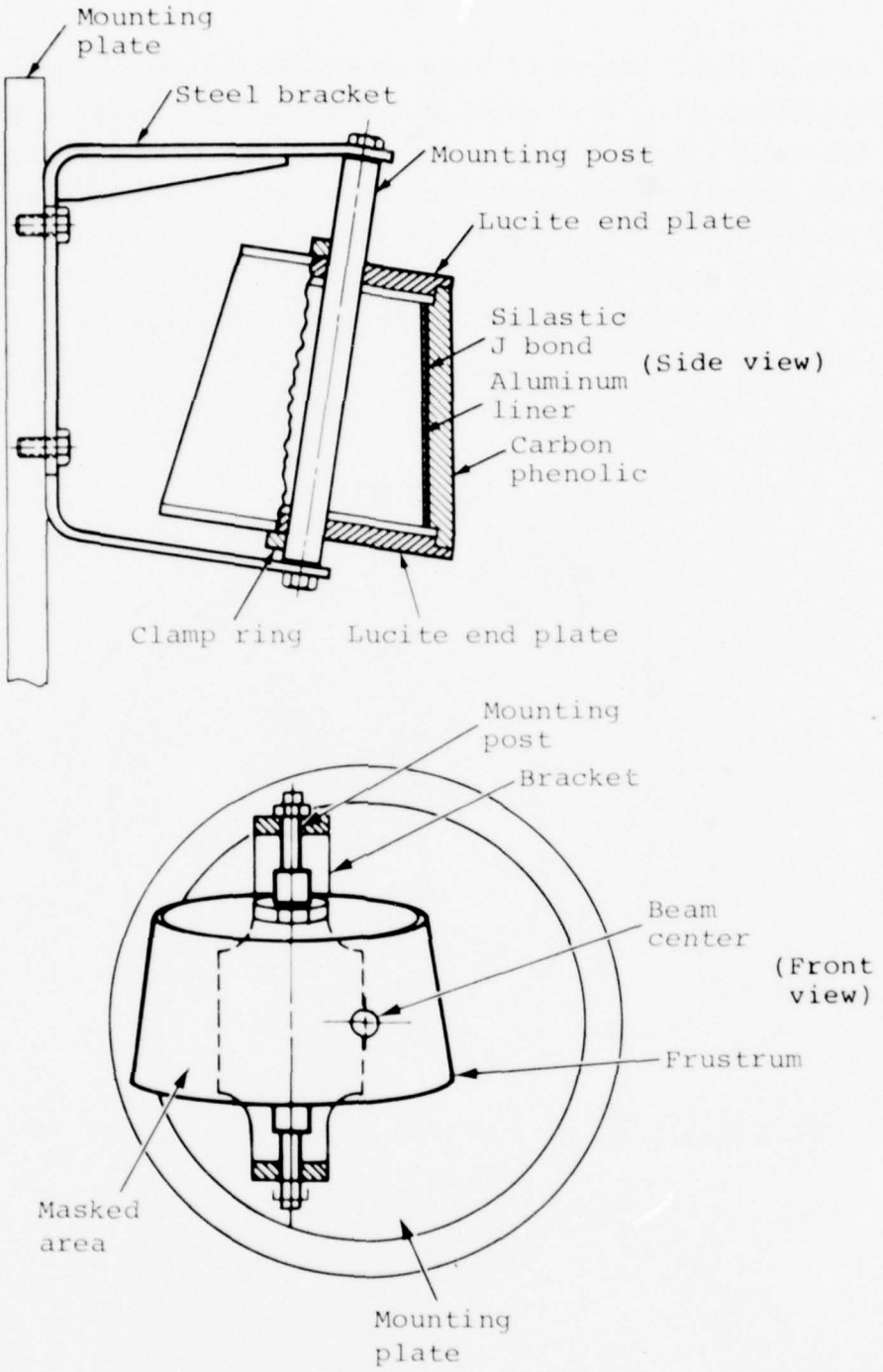


Figure 7 Frustrum mounting hardware.

masked with several layers of thin cardboard to prevent double exposure (Figure 8). This masking technique was chosen because of its adaptability to curved surfaces and was tested during the first experimental series with good results. Although the flat samples were all located at a 10-cm distance from the anode plane, the frusta were positioned with their closest point at 7.5 cm from the anode to compensate for the depth of these samples.

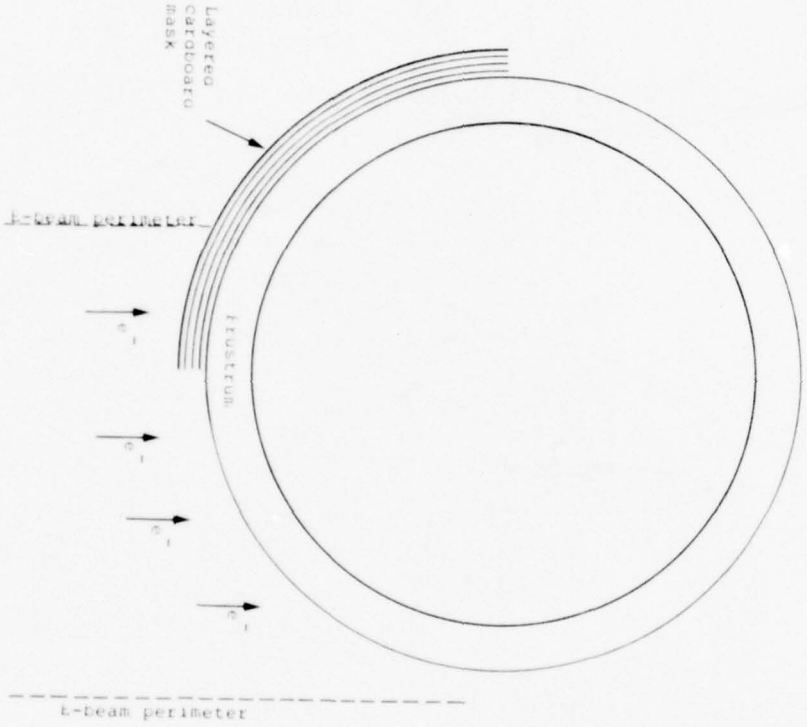


Figure 8 Top section view of masking technique showing e-beam orientation with respect to frustrum sample.

SECTION 3

EXPERIMENTAL DATA

A summary of all data recorded during this experiment is listed in Table 1. As noted in Section 2, the average beam conditions were 320-kV mean diode voltage and 17 cal/cm^2 fluence; the average removal depth was 0.015 cm and average mass loss, 43 mg/cm^2. On all fluence and sample shots a 1-cm^2 area control sample block of CP was exposed near the edge of the beam. The weight of the sample block was recorded before and after the shot in order to monitor the mass loss per unit area. Phenolic removal depth was measured on the main sample with a knife-edge vernier caliper for all flat specimens. On fluence and frusta shots the phenolic removal depth was measured on the 1-cm^2 control samples.

For the frusta samples the average diode fluence was 18 cal/cm^2 with an average mean voltage of 320 kV. A summary of the frusta data is shown in Figure 9. Two sectioned conical samples of CP were available for testing. In one case the cone had an aluminum liner bonded with a 0.1 cm thick Sylastic J bond. The other cone had no liner. All frusta from the lined cone were exposed to the electron beam. On frustum sample 955412-3, however, both exposures were low fluence (12.3 cal/cm^2 average) and the beam appeared somewhat uneven. These shots were repeated with the corresponding section of the unlined cone. No other frusta from the unlined cone were tested. Photos of all irradiated frusta are shown in Figure 10 and the assembled cone is shown in Figure 11.

TABLE 1

DATA SUMMARY

Shot	Shot Type	Anode-Cathode Spacing (cm)	Anode-Target Spacing (cm)	Pulse Charge Voltage (MV)	Diode Voltage Average (KV)	Diode Fluence (cal/cm^2)	Phenolic Removal Depth (cm)	Control Sample Mass Loss (mg)	Peak Stress (Kbar)	Sample I.D.
4361	Short	0	--	1.82	--	--	--	--	--	--
4362	Short	0	--	1.82	--	--	--	--	--	--
4363	Short	0	--	1.82	--	--	--	--	--	--
4364	Fluence	0.7	10	2.28	310	16.0	0.013	--	--	--
4365	Fluence	0.7	10	2.37	300	15.6	0.010	42		
4366	witness plate 0.3 cm poly	0.7	10	2.37	308	16.0	0.015	59		
4367	Quartz gage SR 5x7.5 cm^2 sample	0.7	10	2.46	345	18.6	0.023	--	2.34	K
4368	5x7.5 cm^2 samples 1 SR + 1 CFR	0.7	10	2.00	270	11.7	0.003	--		J,F
4369	Fluence	0.7	10	2.20			0.005	33		
4370	Fluence	0.7	10	2.60	348	20.1	0.018	67		
4371	Fluence	0.7	10	2.64	345	19.3	0.013	69		
4372	Quartz gage 10 cm^2 SR unbacked	0.7	10	3.20	325	19.1	0.023	--	5.02	15
4373	5x7.5 cm^2 samples 1 SR + 1 CFR	0.7	10	2.92	322	16.6	0.015-0.020	53		57/38
4374	Quartz gage CFR 10x10 cm^2 backed	0.7	10	2.92	324	17.0	0.015	53	3.77	6
4375	5x7.5 cm^2, samples 1 SR + 1 CFR	0.7	10	2.92	320	17.6	0.015-0.020	38		E37
4376	Base frusta 1st exp.	0.7	7.5	2.92	330	18.6	0.015	39		955412-4
4377	Fluence	0.7	7.5	2.92	265	14.0	0.018	45		
4378	Base frusta 2nd exp.	0.7	7.5	2.92	315	16.3	0.008	26		955412-4
4379	Quarts gage SR 10x10 cm^2, backed	0.7	10.0	2.92	308	15.9	0.018	53	4.20	16
4380	Frusta, 1st exp.	0.7	7.5	2.92	307	13.7	--	--		955412-3
4381	Quartz gage CFR 10x10 cm^2, backed	0.7	10.0	2.92	275	14.3	0.020	--	3.16	5
4382	Frusta, 2nd exp.	0.7	7.5	2.92	2.53	10.8	0.005	13		955412-3
4383	Fluence	0.7	10.0	2.92	3.29	17.4	0.028	79		
4384	CFR sample, 10 cm x 10 cm, backed	0.7	10.0	2.92	342	21.3	0.018	37		A
4385	Frusta, 1st exp.	0.7	7.5	2.92	304	16.1	0.013	25		955412-2
4386	Frusta, 2nd exp.	0.7	7.5	2.92	370	19.9	0.010	31		955412-2
4387	Tip frusta 1st exp.	0.7	7.5	2.92	316	16.8	--	--		955412-1
4388	Fluence Tip frusta	0.7	10.0	--	352	18.3	0.025	73		
4389	Tip frusta 2nd exp.	0.7	7.5	2.55	365	18.1	--	--		955412-1
4390	Quartz gage SR 10x10cm^2, backed	0.7	10.0	2.55	317	19.5	0.036	44	2.57	C
4391	Frusta (unbacked)	0.7	10.0	2.55	Machine Malfunction					
4392	Fluence	0.7	10.0	1.74	Machine Malfunction					
4393	Fluence	0.7	10.0	2.73	349	21.0	0.033	157		
9394	Frusta, unbacked 1st exp.	0.7	7.5	2.55	300	18.1	--	--		
4395	5x7.5 sample SR	0.7	10.0	2.55	331	19.0	0.023	--		56
4396	Frusta, unbacked 2nd exp.	0.7	7.5	2.56	307	19.1		--		
Series Average		0.7	1.0	2.71	318	16.9	0.015	43		

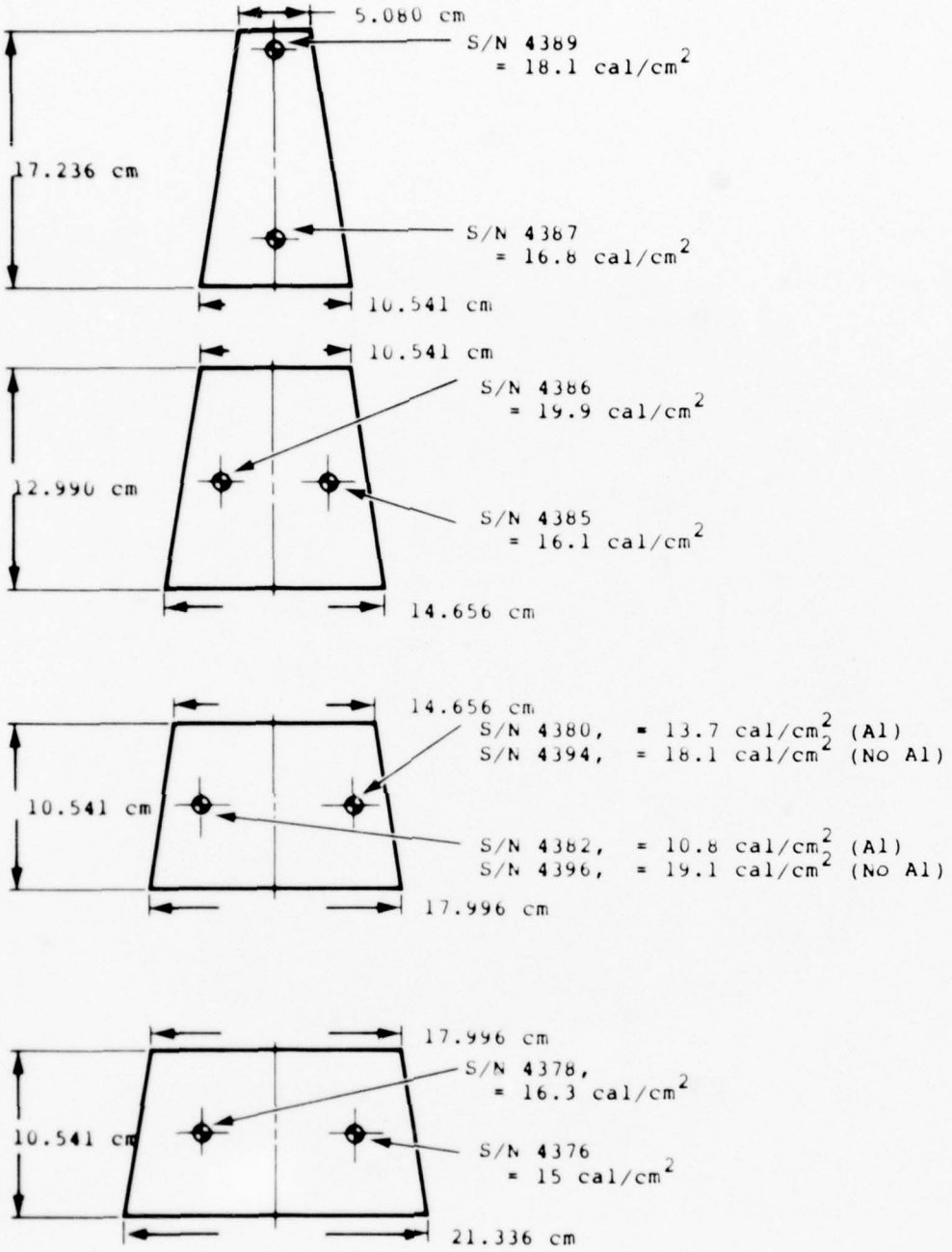


Figure 9 Beam exposure pattern for frustra.

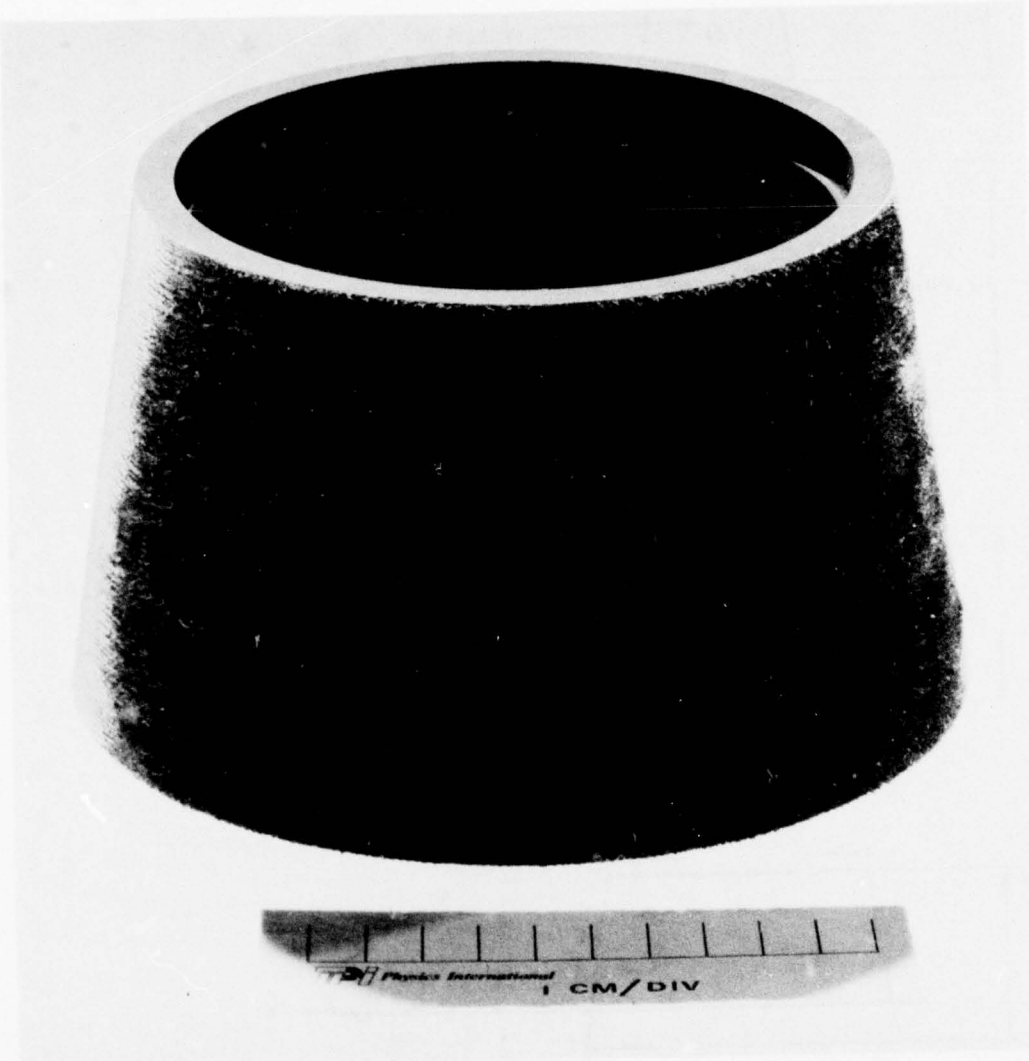


Figure 10 Individual frusta.

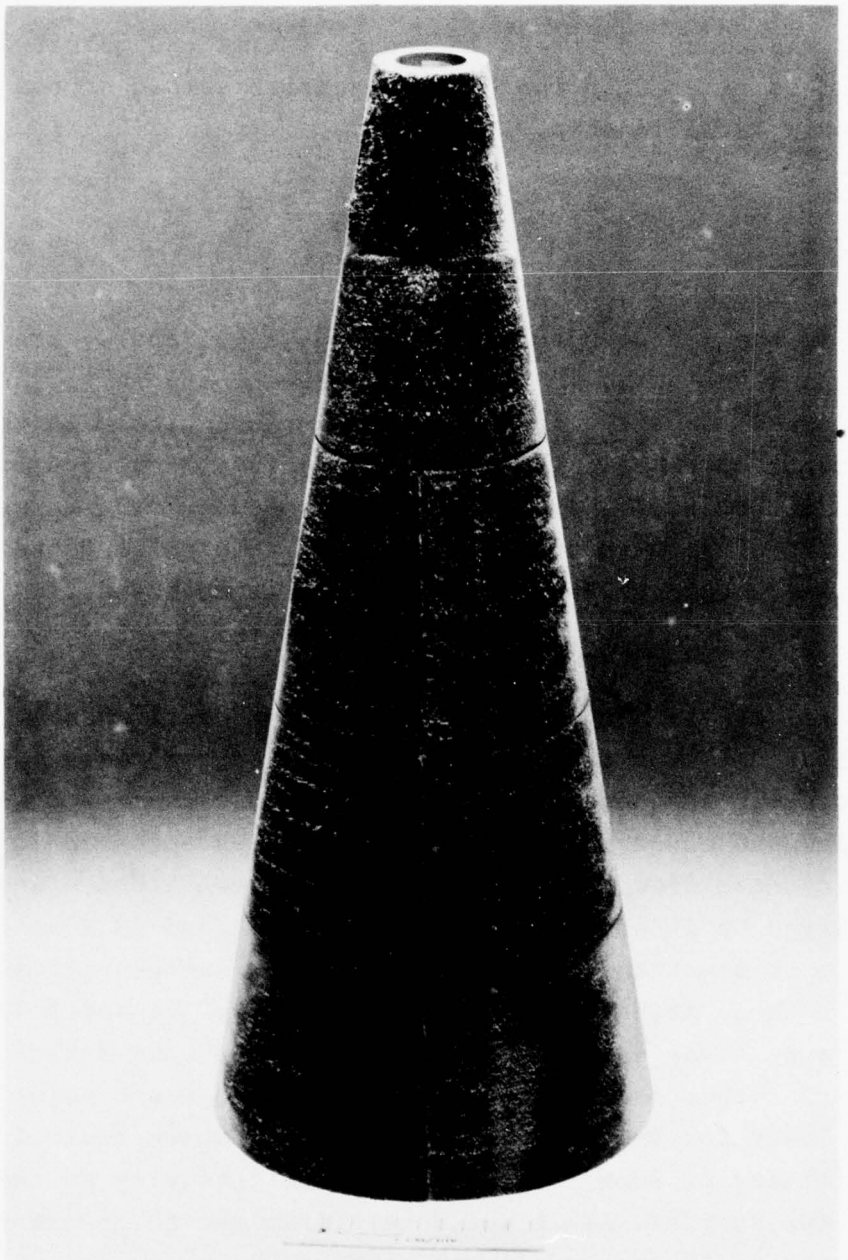


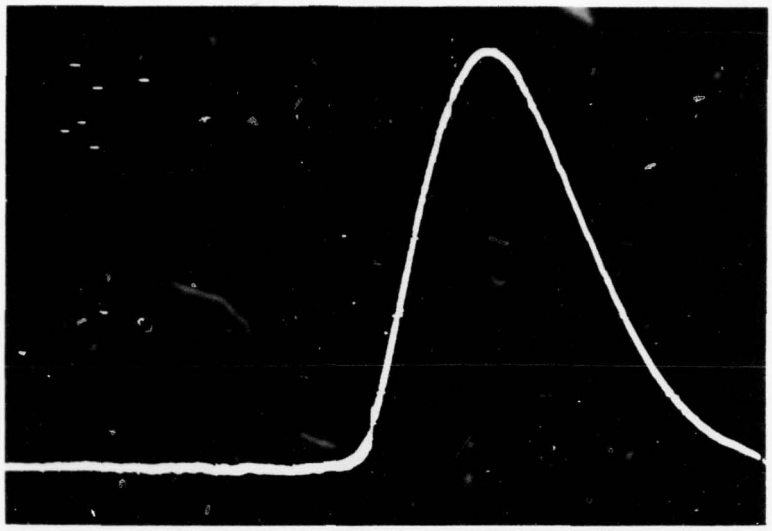
Figure 11 Assembled Cone.

The raw quartz gage data from this test are shown in Figures 12, 13, and 14, with a summary of the reduced data in Table 2. The measured stress is the stress in the quartz gage itself and is related to the carbon phenolic sample stress by the following relationship,

$$\sigma_s = \sigma_g \frac{P_s C_s + \rho_g C_g}{2 \rho_g C_g}$$

where σ_g is the measured stress in the gage, ρ_g and C_g are the density and sound speed in the gage material, and σ_s, ρ_s and C_s are the stress, density, and sound speed respectively in the carbon phenolic sample. The gage is made from x-cut quartz and has a density of 2.65 g/cm^3 and a sound speed of 5.73 mm/μs. For the carbon phenolic the density was 1.45 g/cm^3 and the sound speed varied between 3.40 and 3.87 cc/μs, as measured from the gage records.

A total of six samples were tested with quartz gages, two CFR and four SR. For the CFR samples, the stress measurements were consistent and the relationship between fluence and peak stress appeared constant. The four SR samples appeared to be divided into two groups where the ratio between fluence and peak stress varied by a factor of two. Shots 4372 and 4379 were mutually consistent and exhibited stress-to-fluence ratios similar to those observed for the CFR samples. On shots 4367 and 4390 the stress was well below what would have been anticipated based on the other measurements. The observed sound velocity was also lower for those shots (3.40 mm/μs), which could indicate the possibility of some reduced mechanical integrity on the part of these two samples. This would be sufficient to reduce the measured stress to the levels observed.



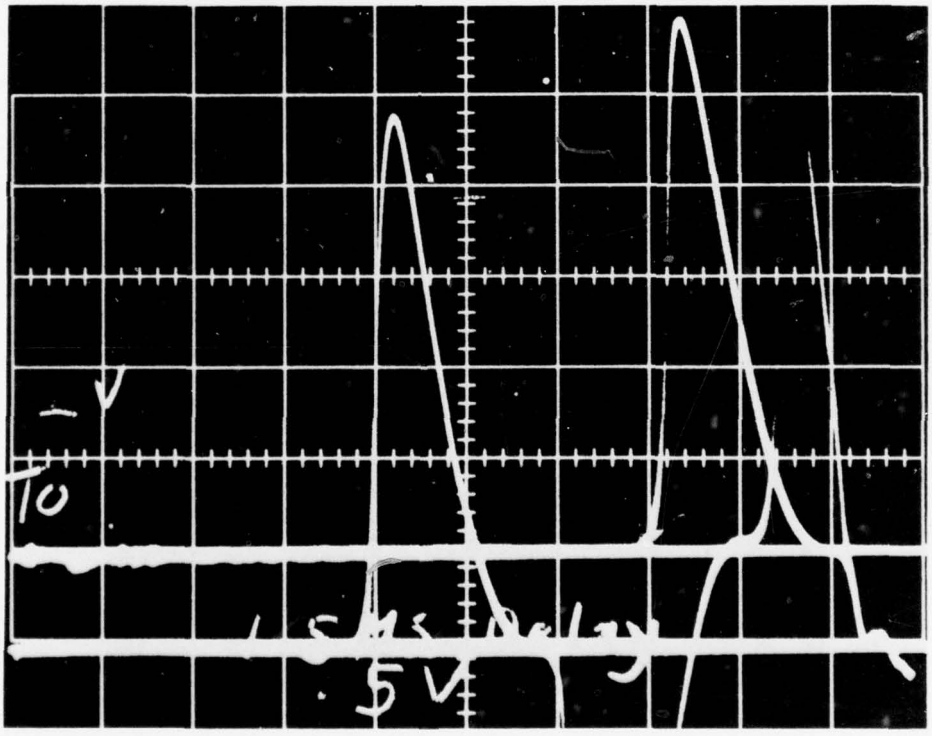


Figure 12 Quartz gage data (shots 4367 and 4372).

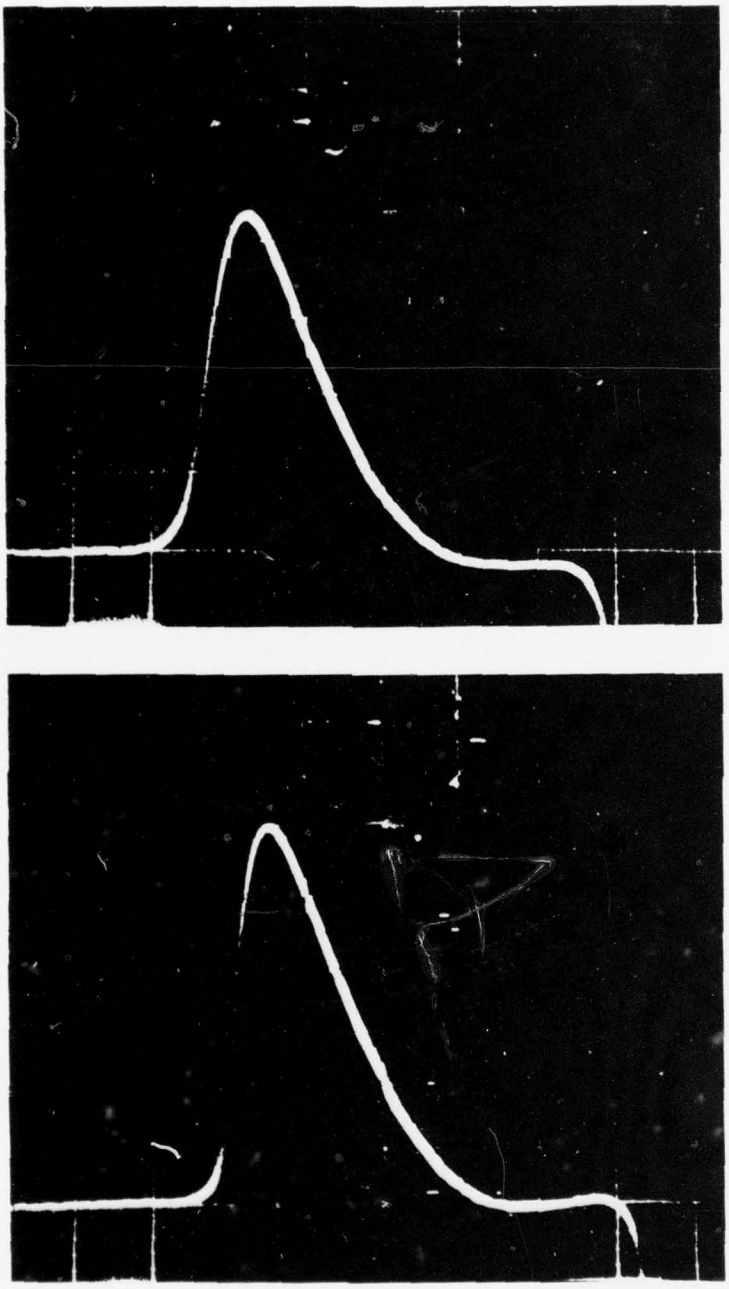


Figure 13 Quartz gage data (shots 4374 and 4379).

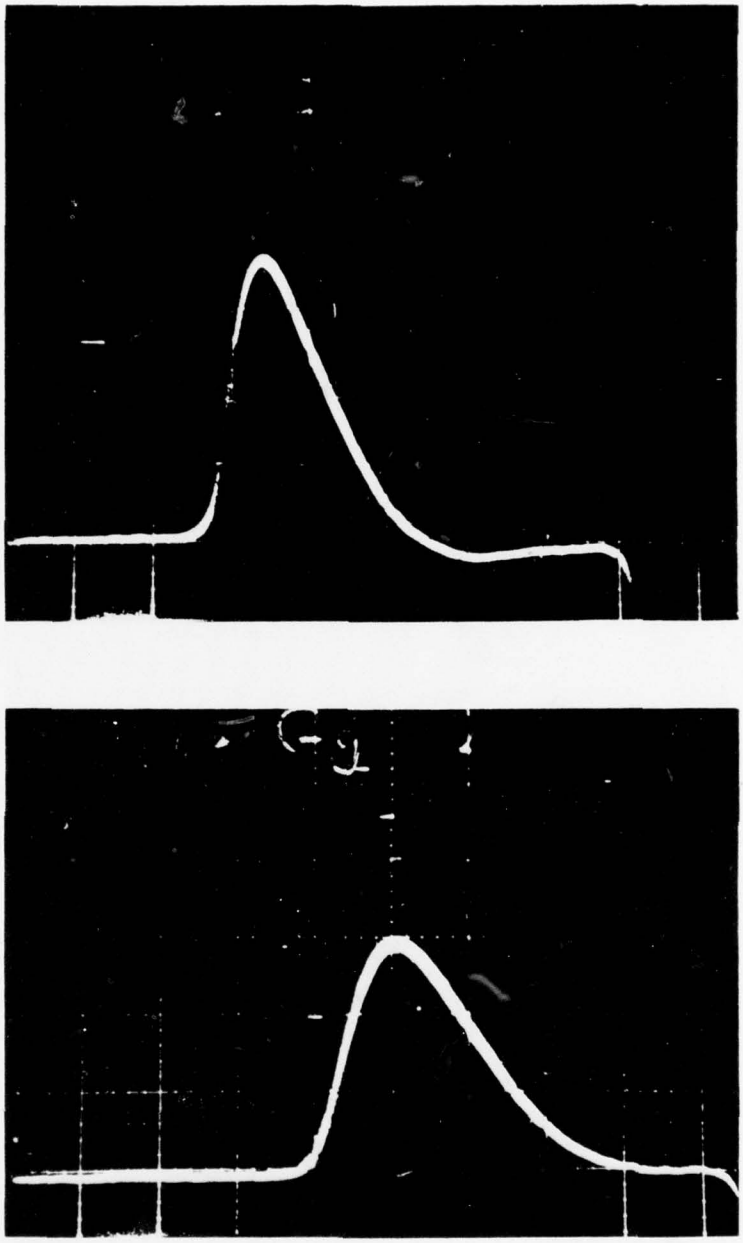


Figure 14 Quartz gage data (shots 4381 and 4390).

TABLE 2

QUARTZ GAGE DATA

Shot	Diode Mean Voltage (kV)	Diode Fluence (cal/cm^2)	Peak Stress (kbar)		Pulse Width (ns)	Pulse Velocity mm/μs	Sample Type	Sample I.D.
			Gage	Sample				
4367	345	18.6	2.34	1.55	496	3.40	SR	K
4372	330	19.1	4.93	3.35	364	3.76	SR	15
4374	323	17.0	3.77	2.58	310	3.87	CFR	6
4379	312	15.9	4.20	2.85	304	3.75	SR	16
4381	279	14.3	3.16	2.14	264	3.74	CFR	5
4390	335	19.5	2.57	1.71	405	3.46	SR	C

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

The OWL II generator, in conjunction with the large-area beam hardware, generated a reproducible uniform electron beam capable of removing between 0.013 and 0.025 cm depth of phenolic from carbon phenolic ablator surfaces. The beam had a diameter of 19 cm (280 cm^2), which constitutes a 40-percent improvement in beam area over that used to obtain the same removal conditions during the previous experiment. Any further substantial increase in area would require a major redesign of the diode hardware. With new hardware it is possible that a factor of almost four increase in beam area may be possible on the OWL II' configuration on the generator.

A second area of possible improvement is related to the masking of samples when multiple beam exposures are planned on a single specimen. On all frusta exposed during this series a narrow ridge of phenolic remains between the two beam exposures in spite of efforts to eliminate this through repositioning of the mask. Subsequent tests by PDA will determine whether these ridges present a problem in ablation or aerodynamic experiments. If the ridge effect is significant, some experimental effort should be dedicated to developing a more efficient mask prior to further sample irradiation.

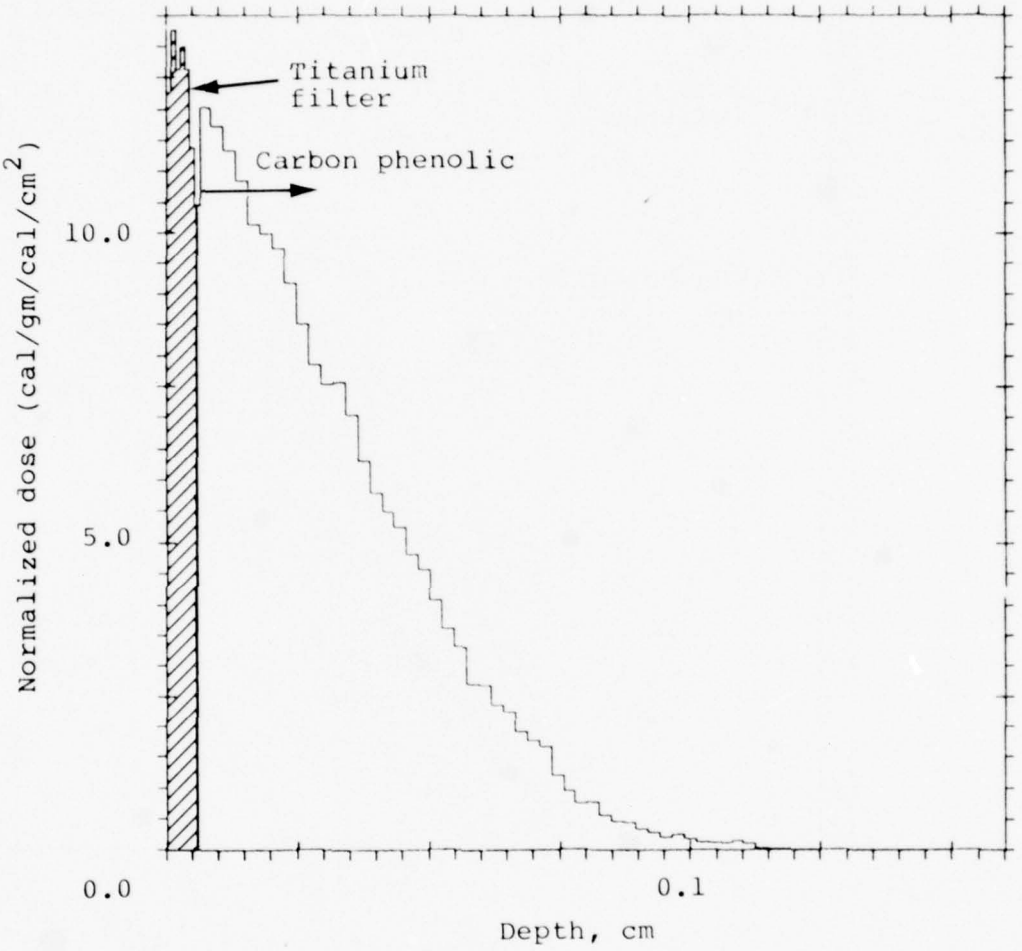
REFERENCES

1. K. Triebes, C. Stallings, and J. Shea, Electron Beam Conditioning of Carbon Phenolic Ablator Surface, DNA 4522F, June 1978.

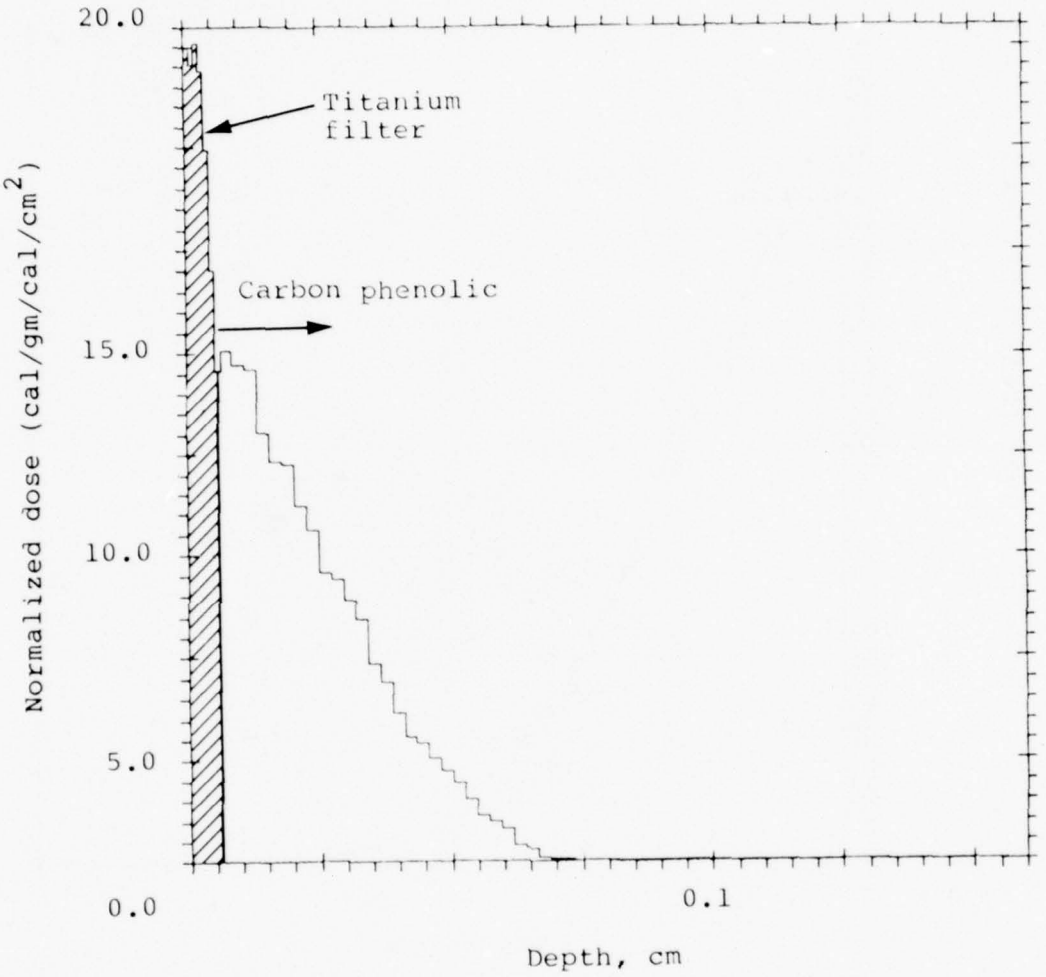
APPENDIX

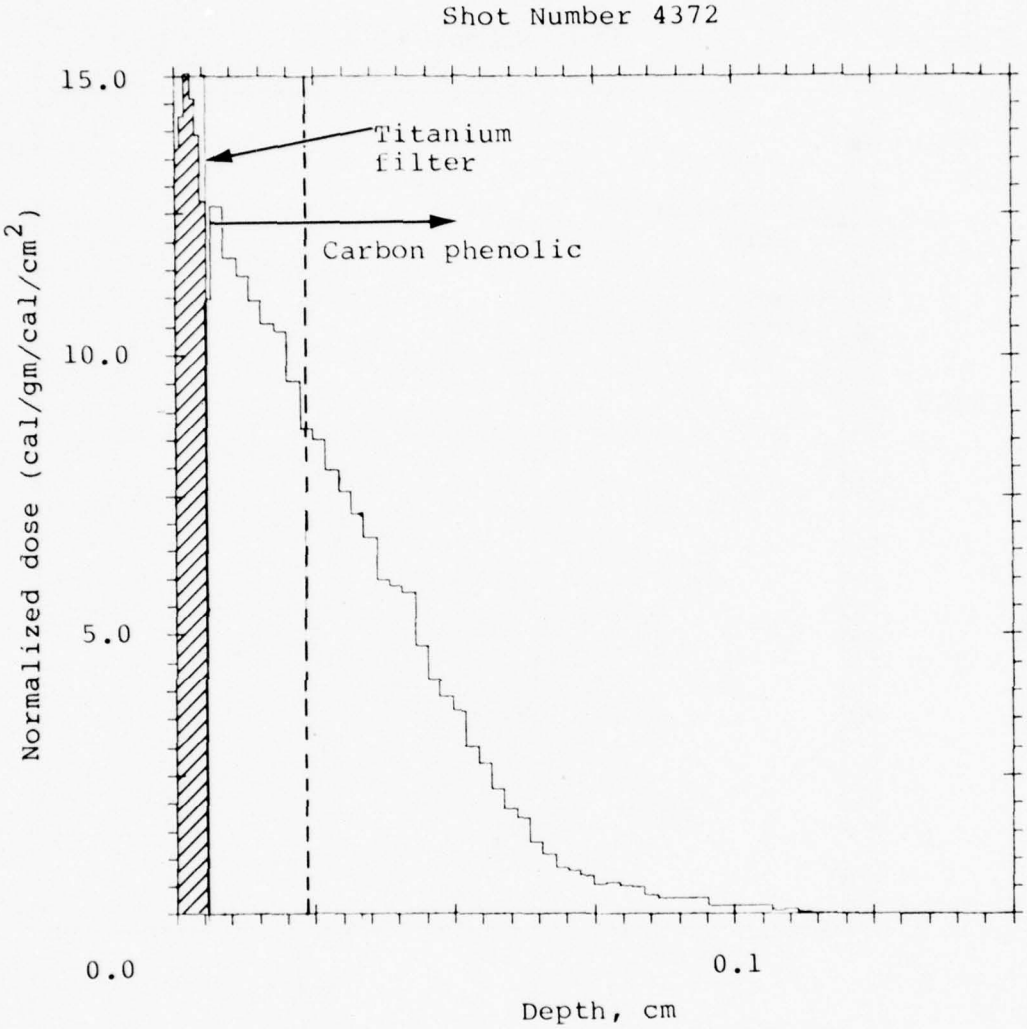
CALCULATED DEPTH DOSE PROFILES

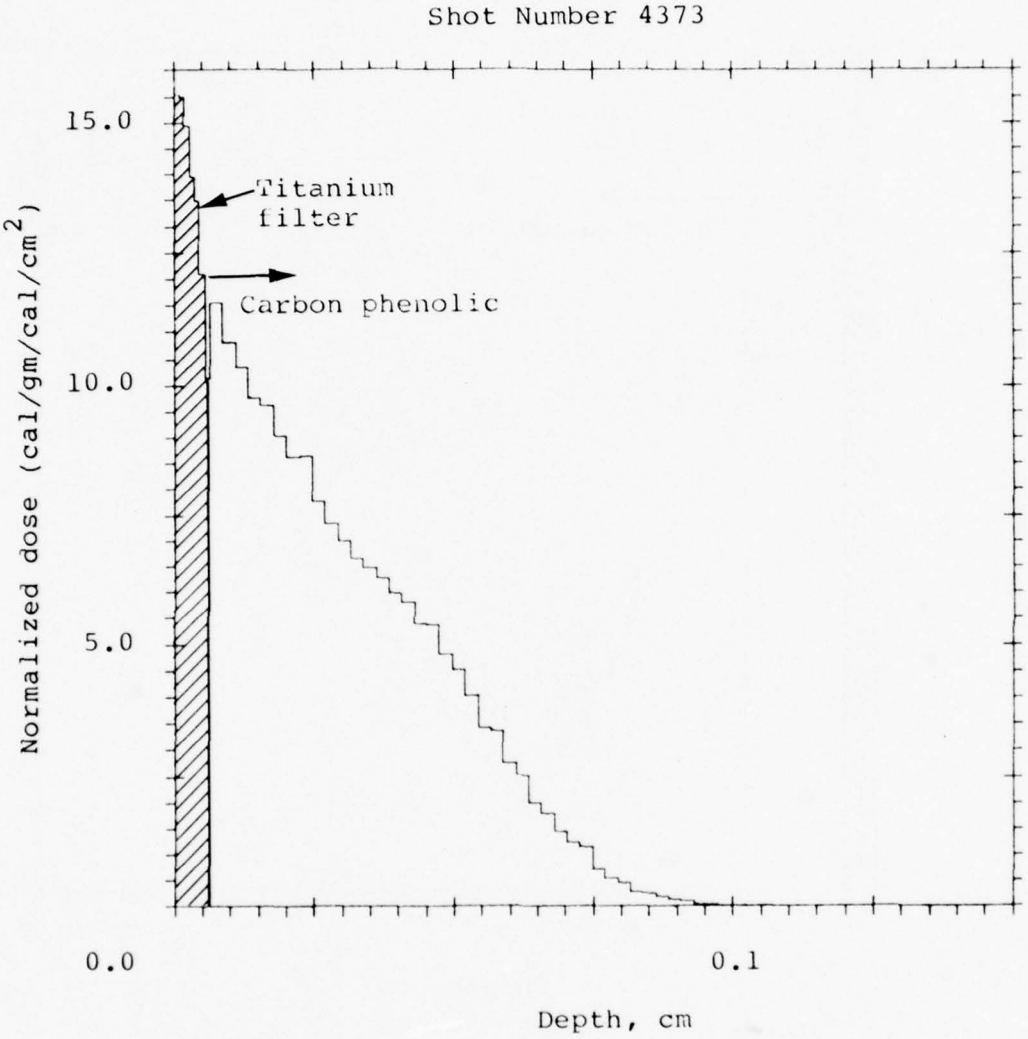
Shot Number 4367

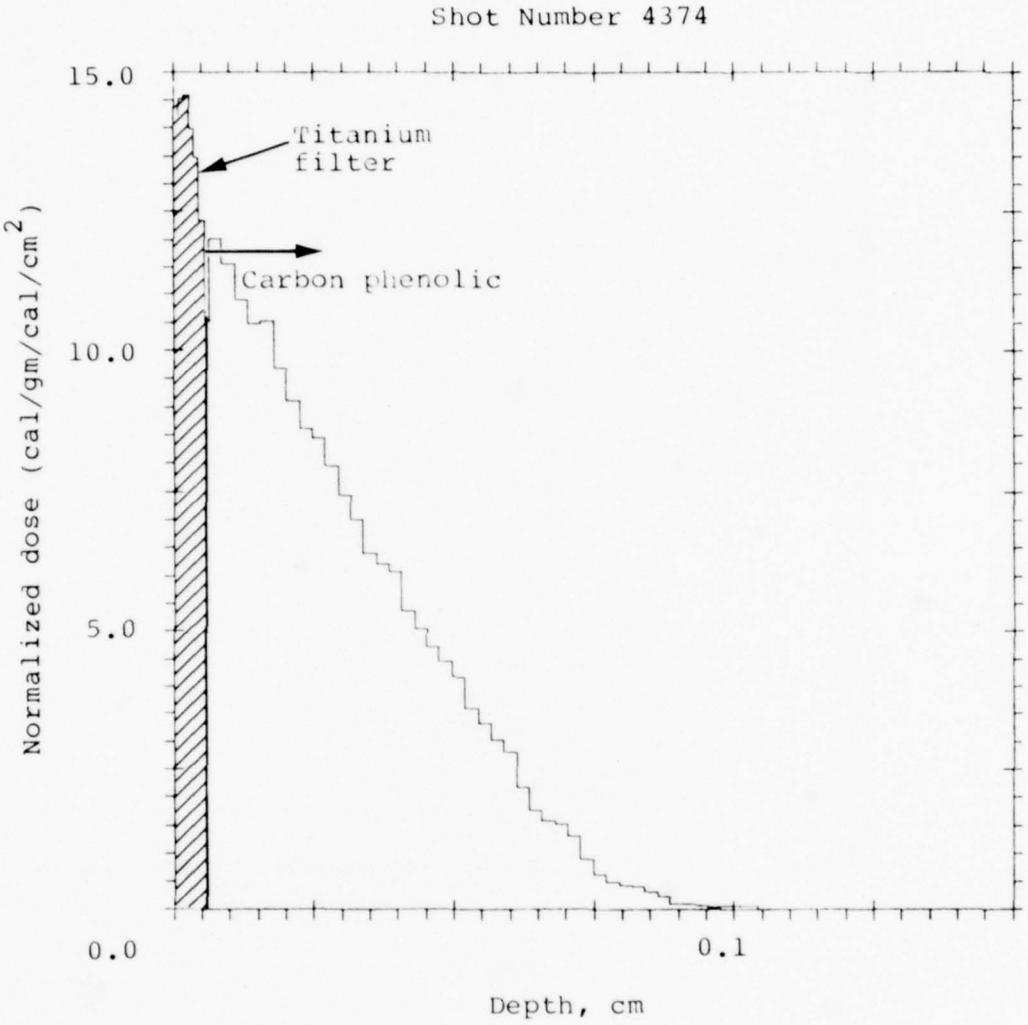


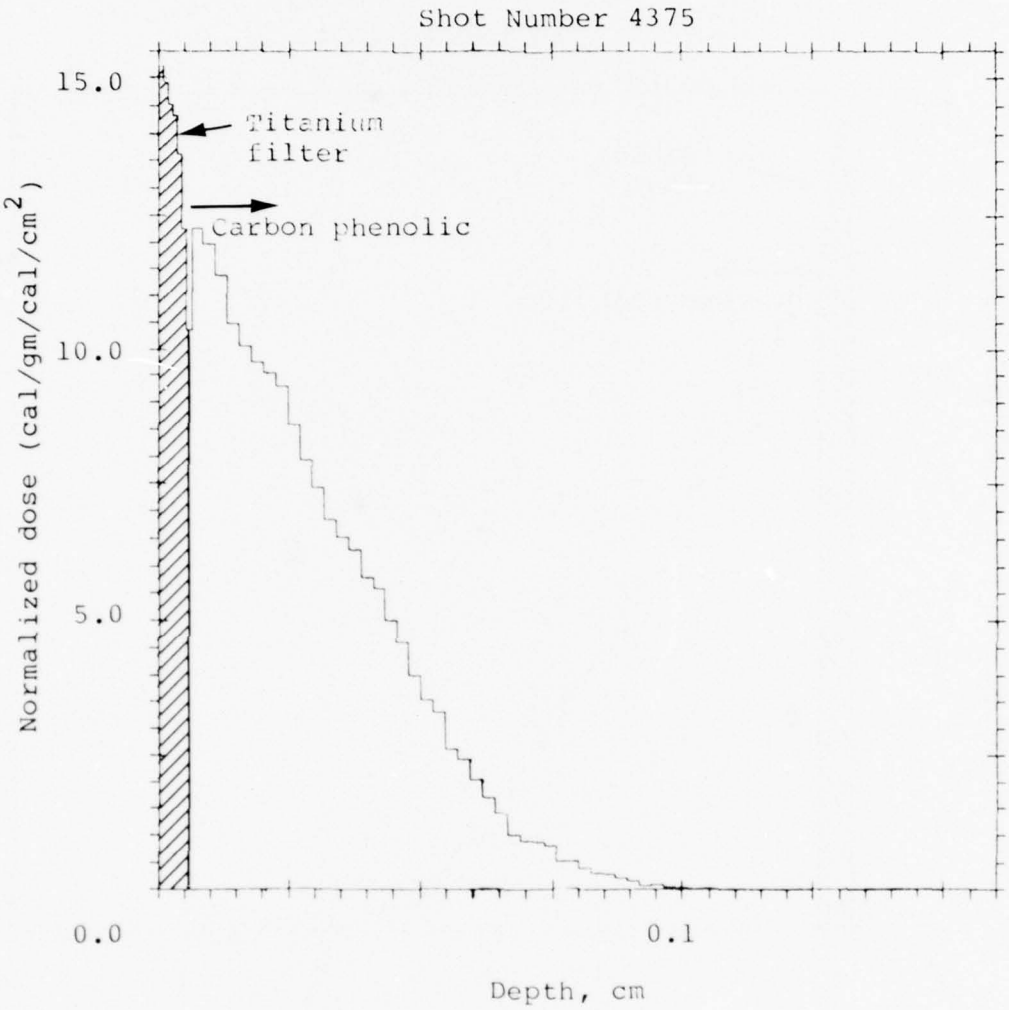
Shot Number 4368

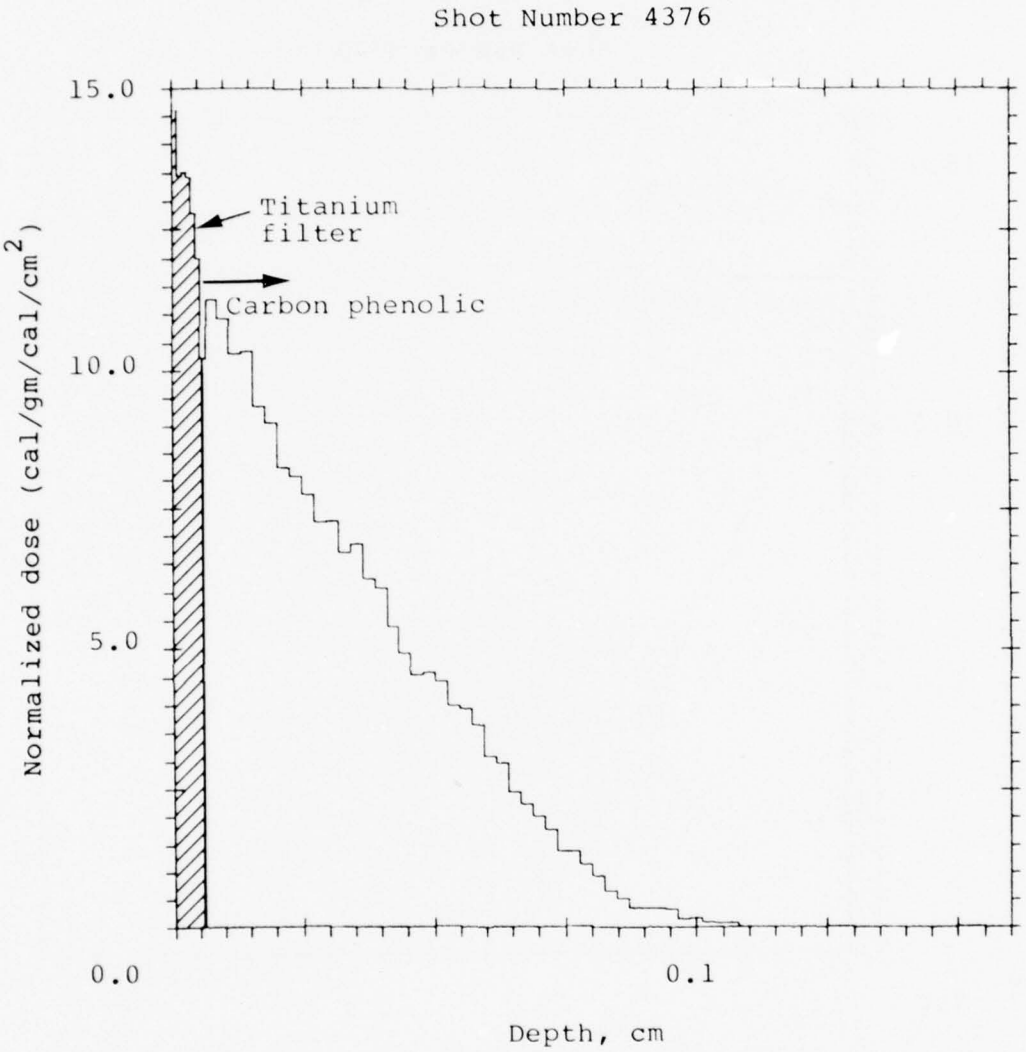



Shot Number 4372
15.0
10.0
5.0
0.0
0.1
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
Depth, cm

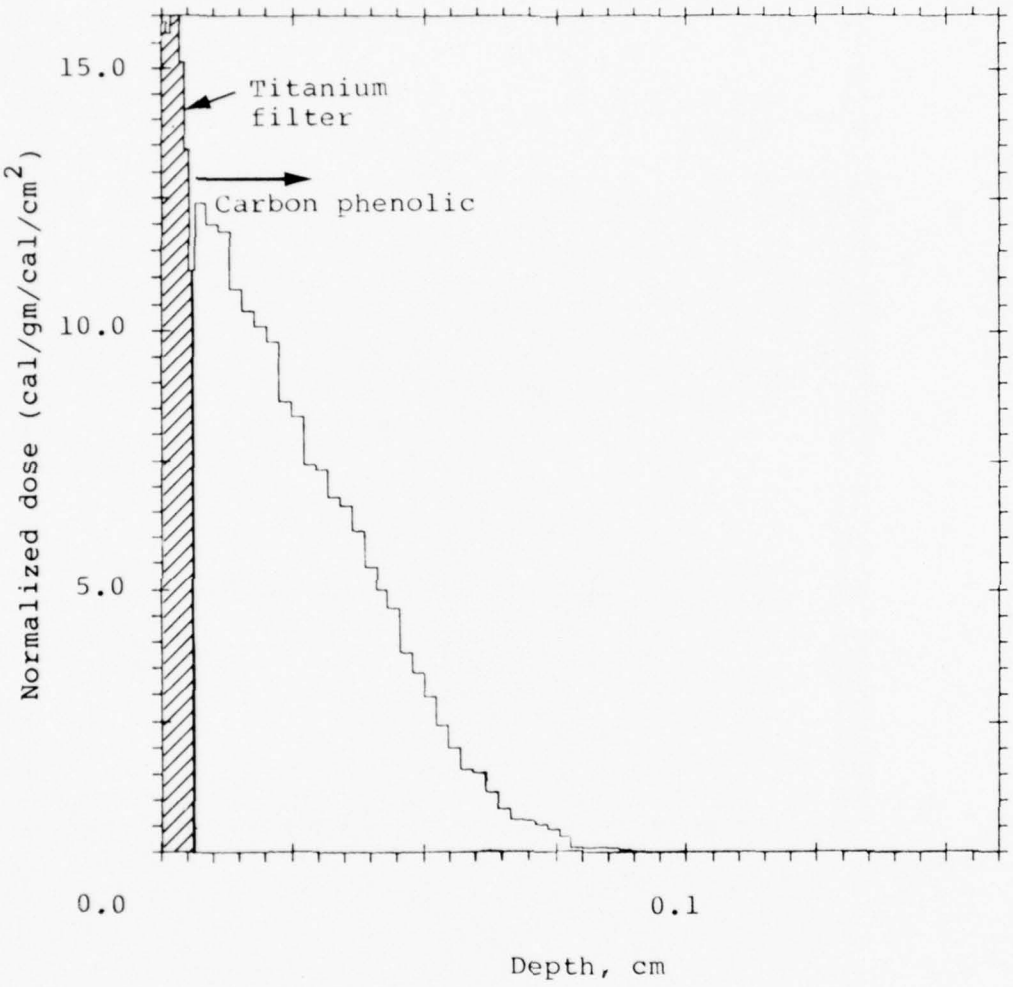

Shot Number 4373
15.0
10.0
5.0
0.0
Normalized dose (cal/gm/cal/cm^2)
Titanium filter
Carbon phenolic
0.1
Depth, cm


Shot Number 4374
15.0
10.0
5.0
0.0
Titanium
filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
0.1
Depth, cm

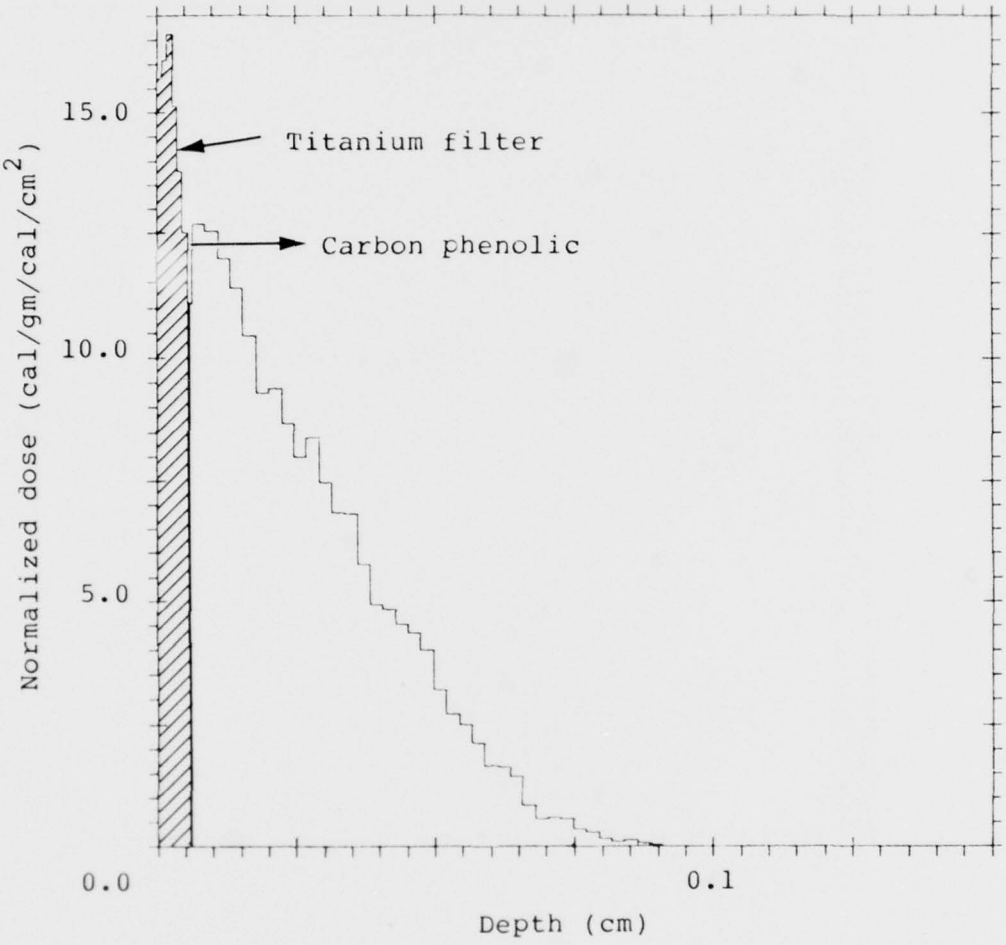

Shot Number 4375
15.0
10.0
5.0
0.0
0.1
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
Depth, cm

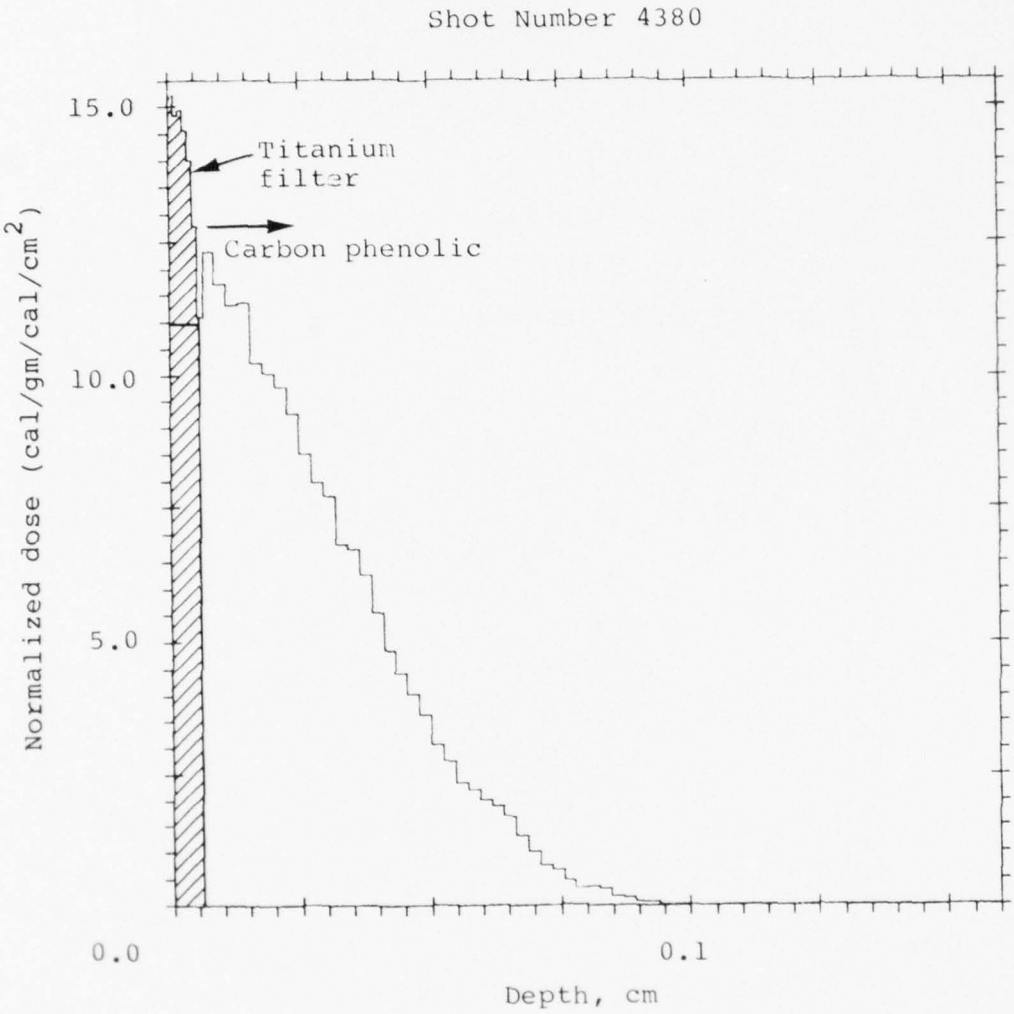

Shot Number 4376
15.0
10.0
5.0
0.0
0.1
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
Depth, cm

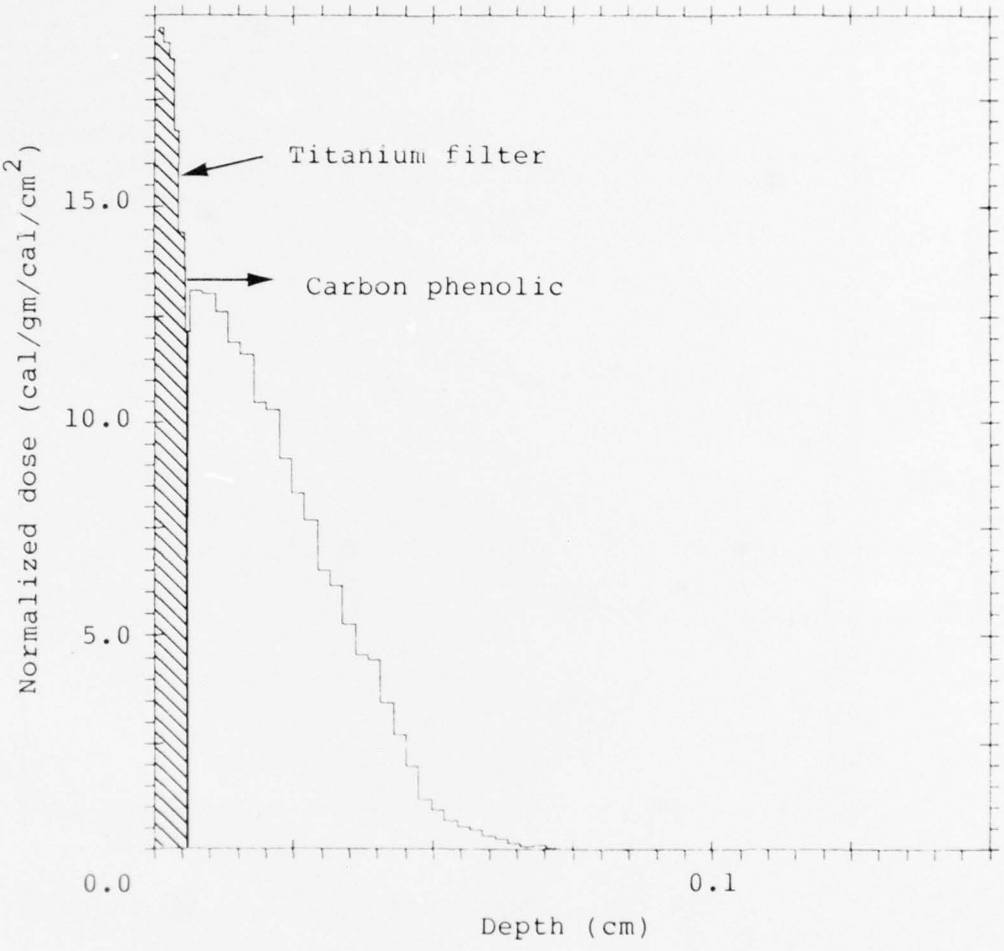
Shot Number 4378



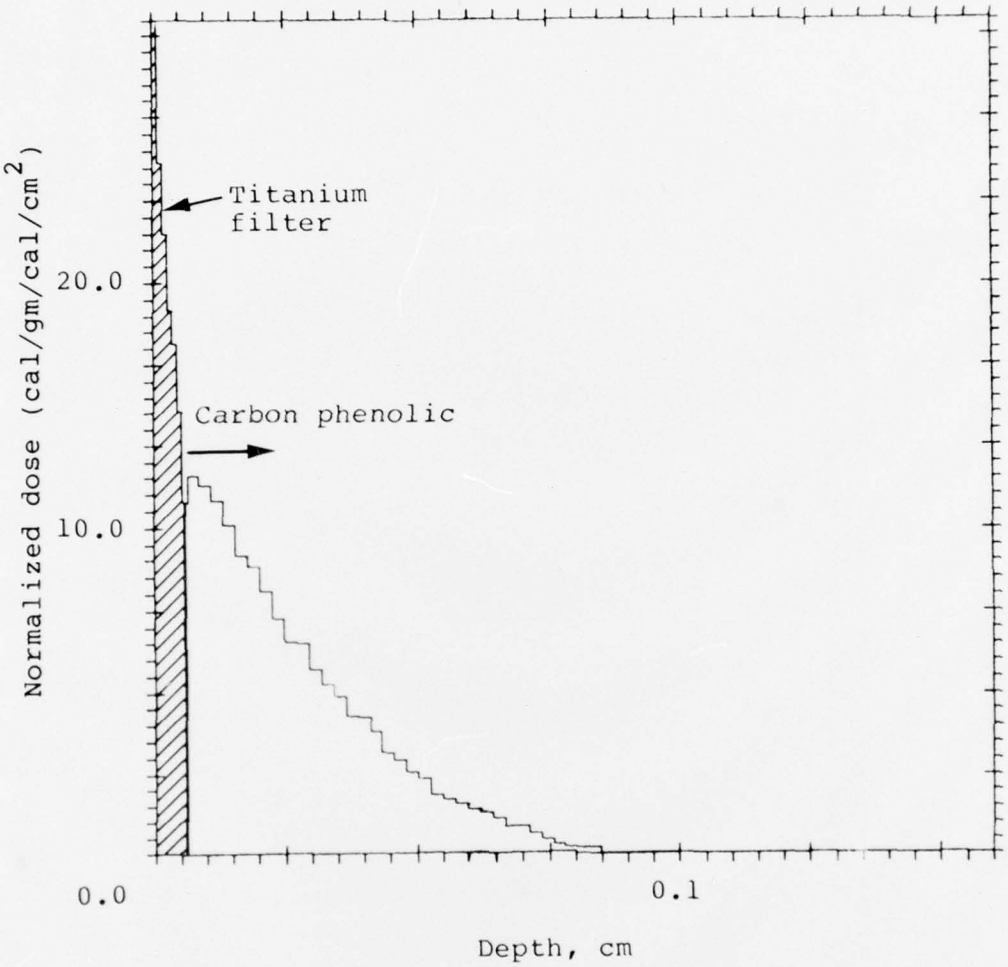
Shot Number 4379

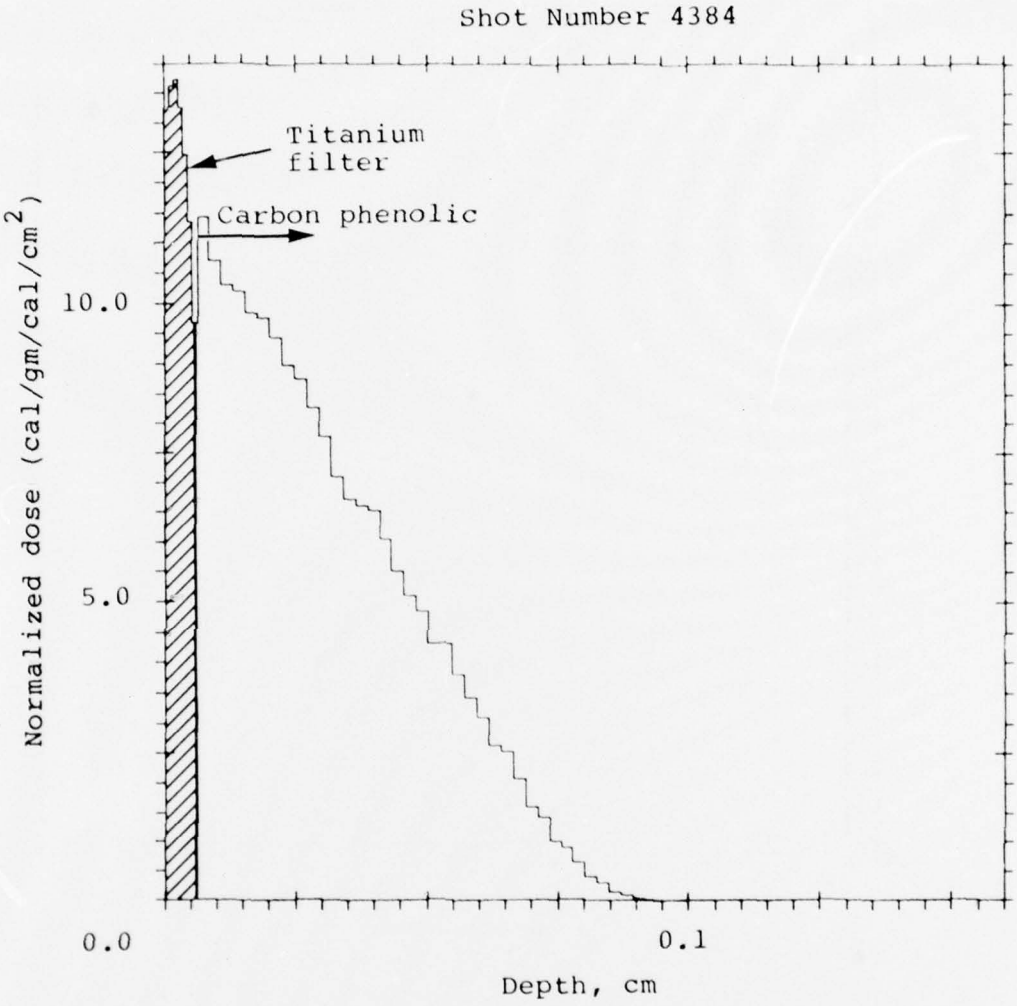


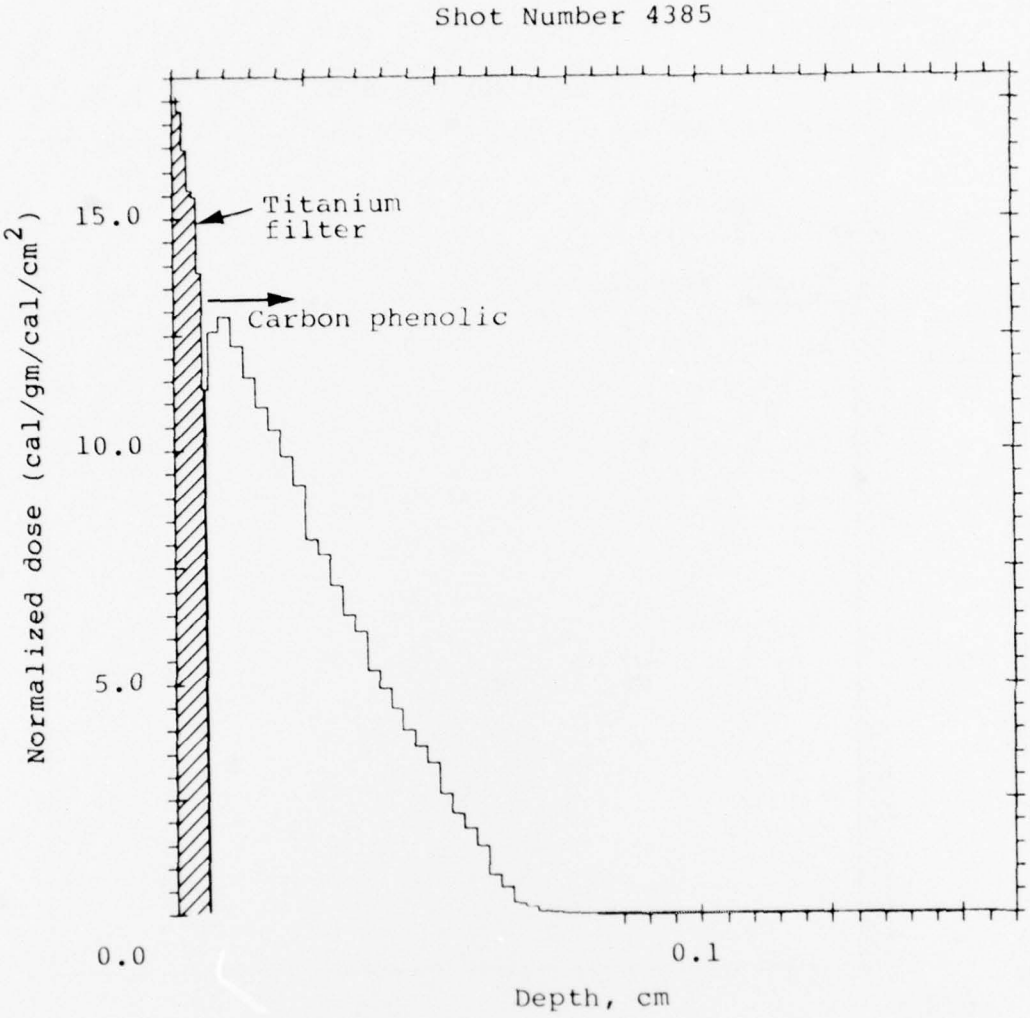

Shot Number 4380
15.0
10.0
5.0
0.0
0.1
Titanium
filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
Depth, cm


Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
15.0
10.0
5.0
0.0
0.1
Depth (cm)

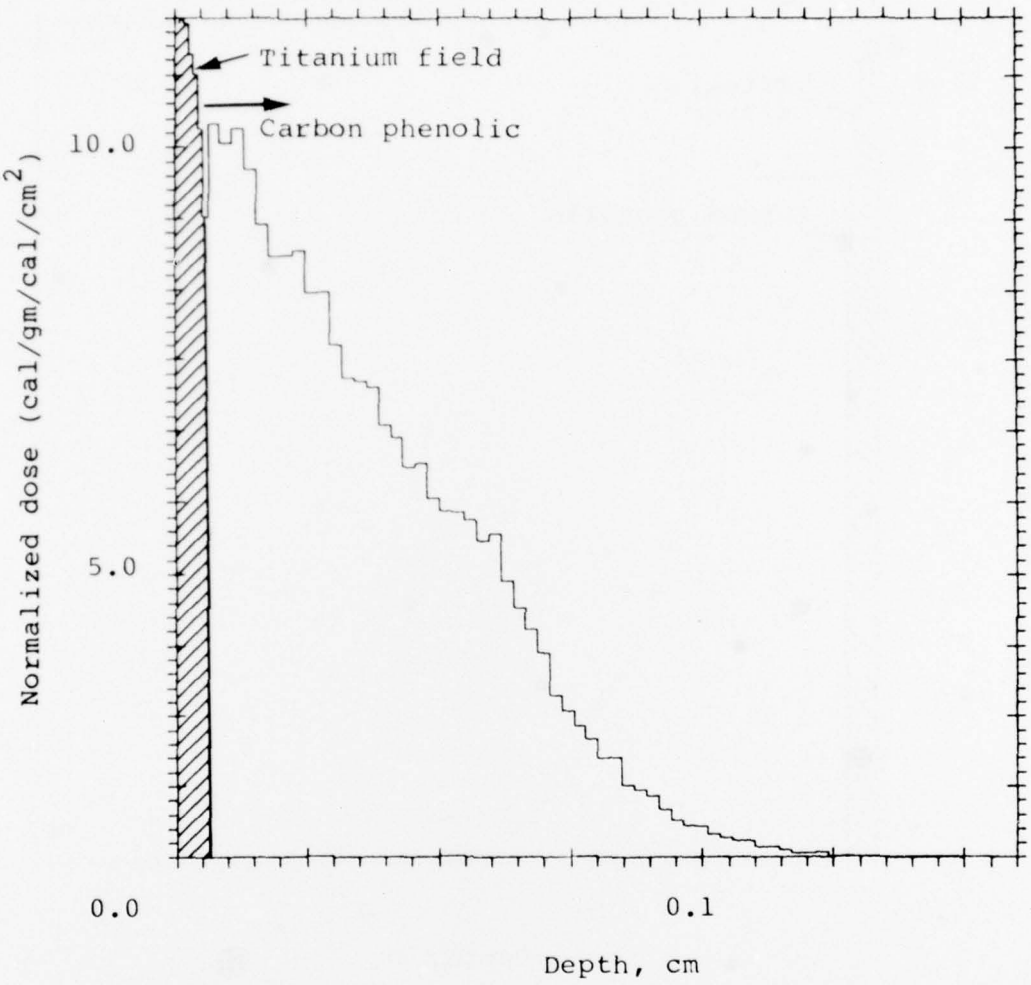
Shot Number 4382

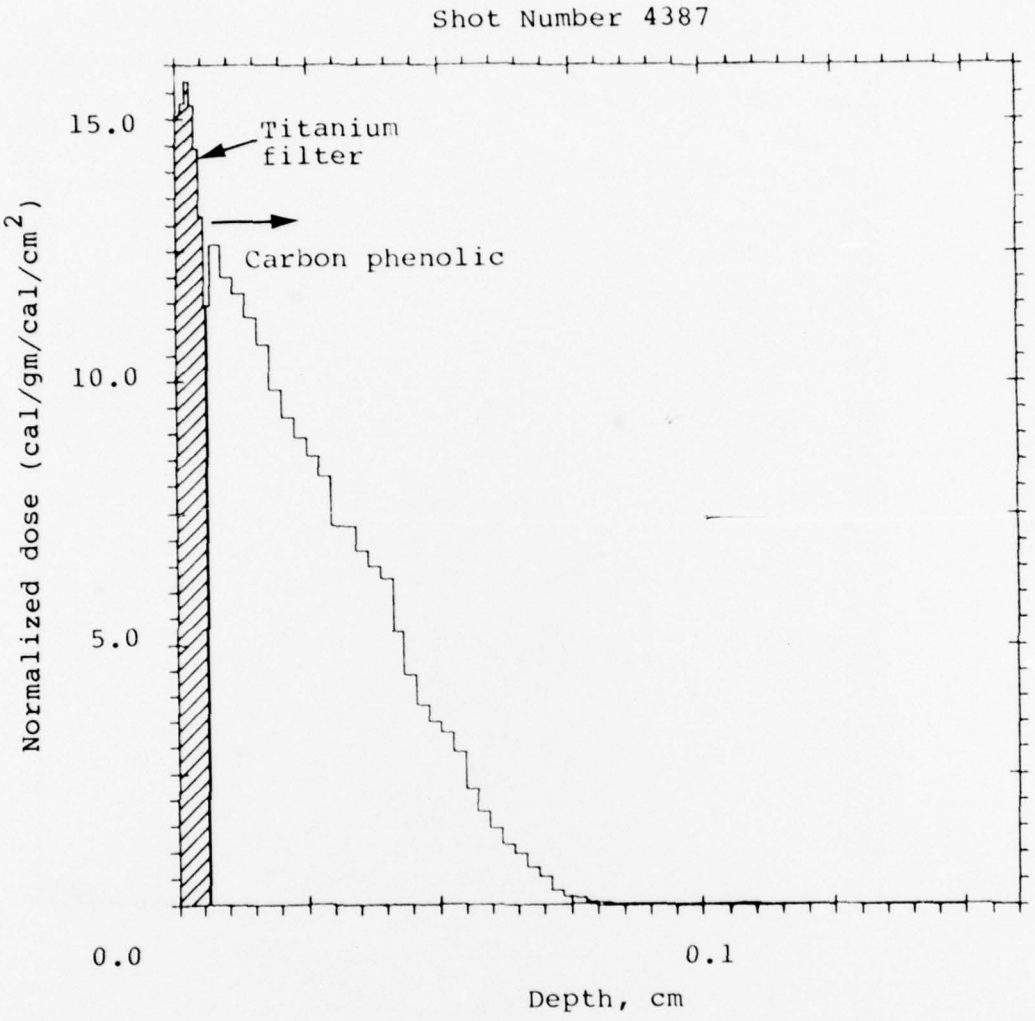


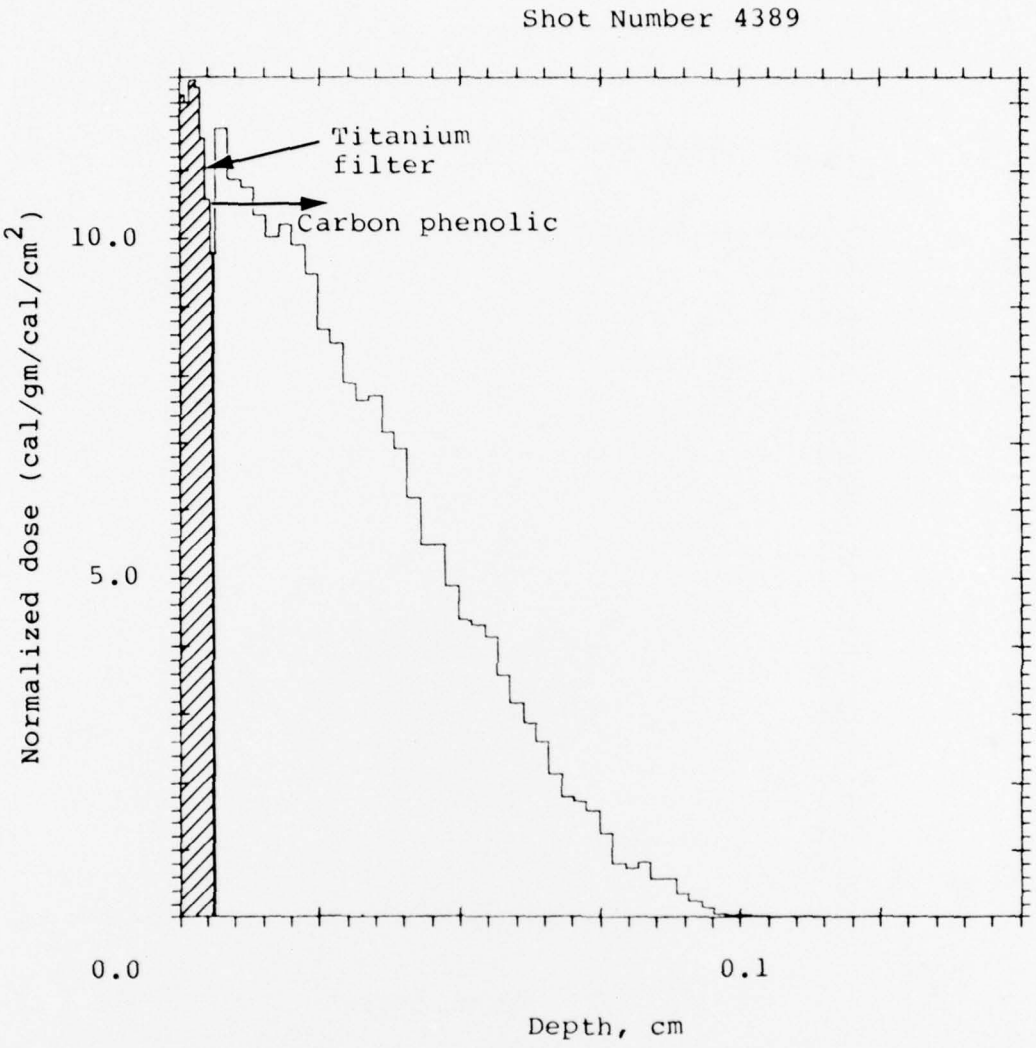

Shot Number 4384
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
10.0
5.0
0.0
0.1
Depth, cm

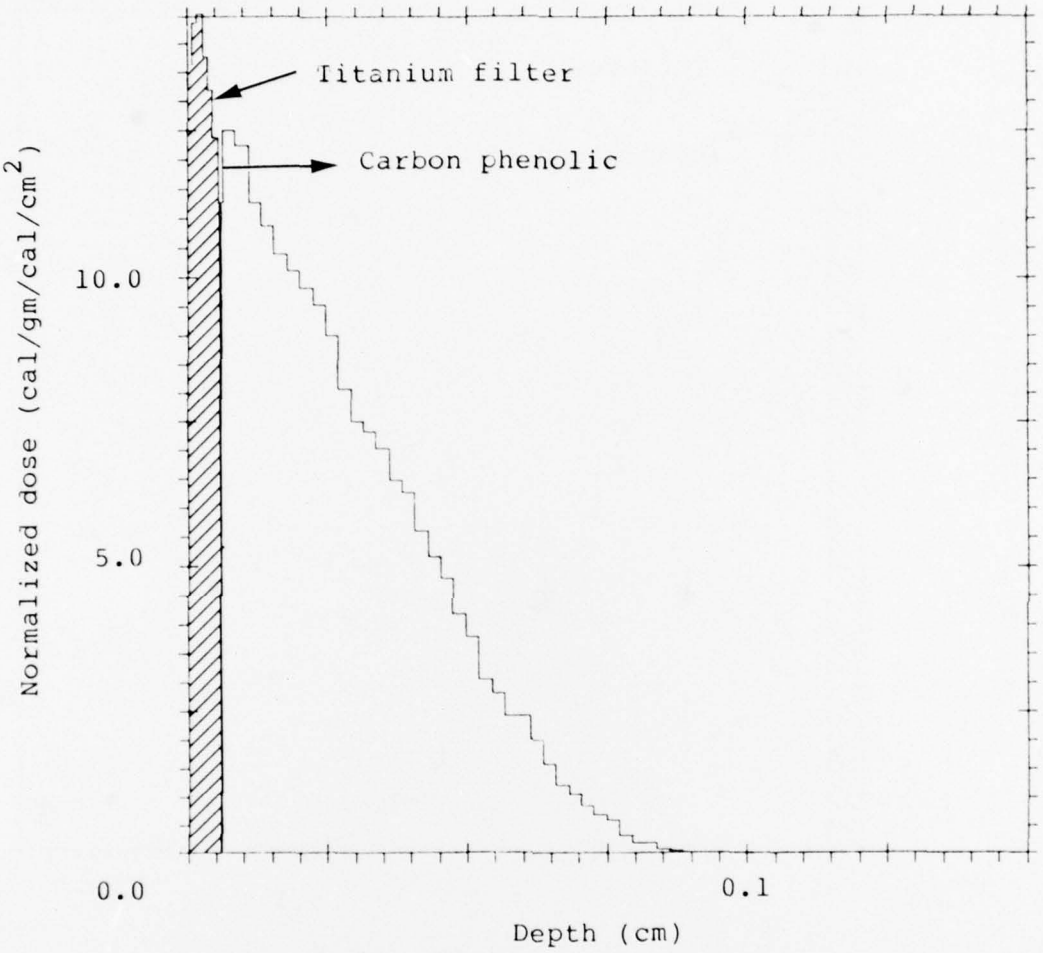

Shot Number 4385
Titanium filter
Carbon phenolic
15.0
10.0
5.0
0.0
0.1
Normalized dose (cal/gm/cal/cm^2)
Depth, cm

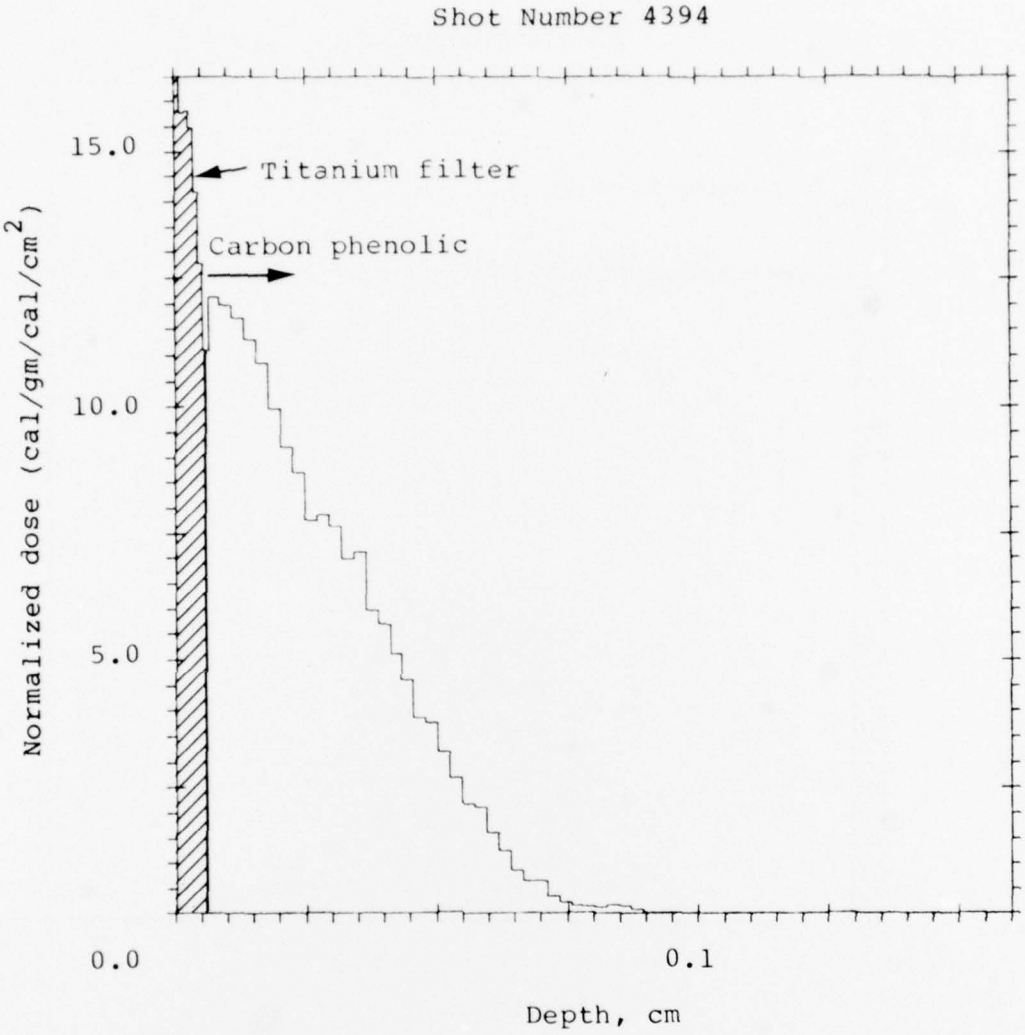
Shot Number 4386

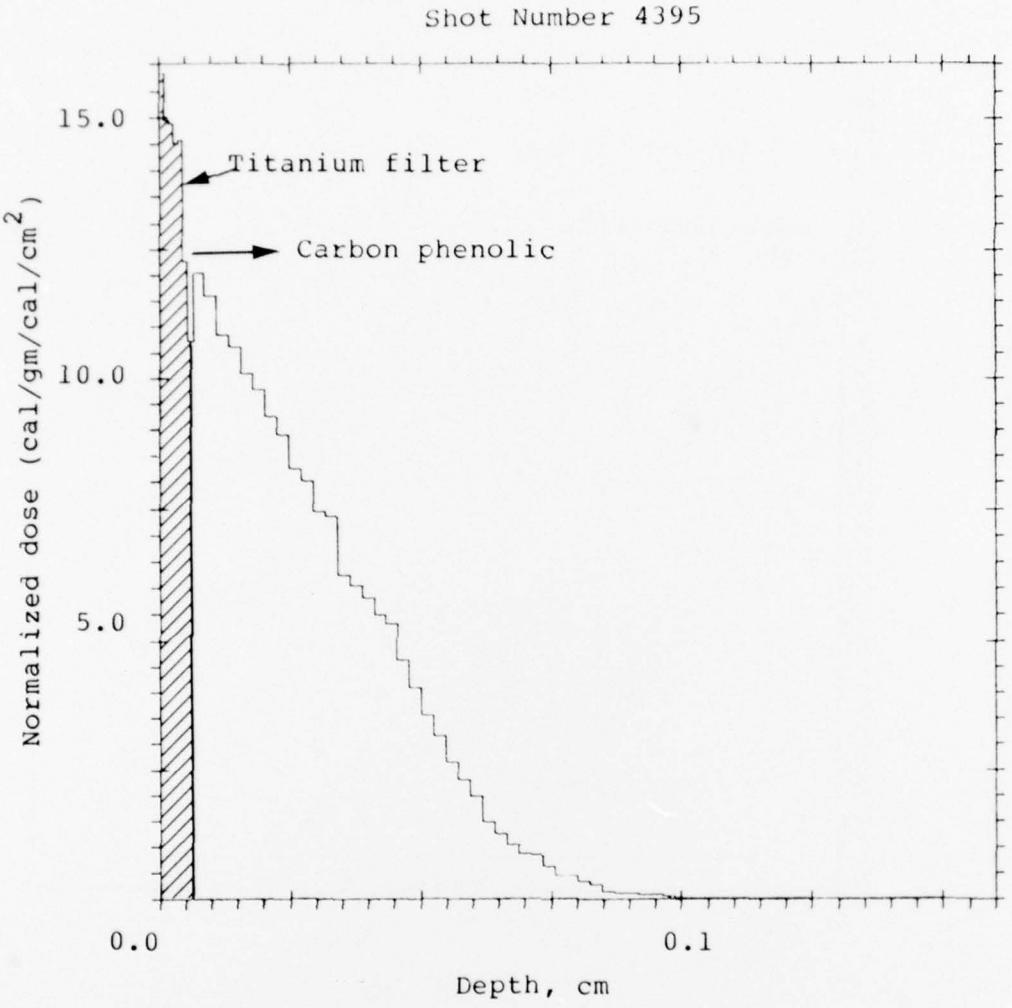



Shot Number 4387
15.0
10.0
5.0
0.0
Titanium
filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
0.1
Depth, cm

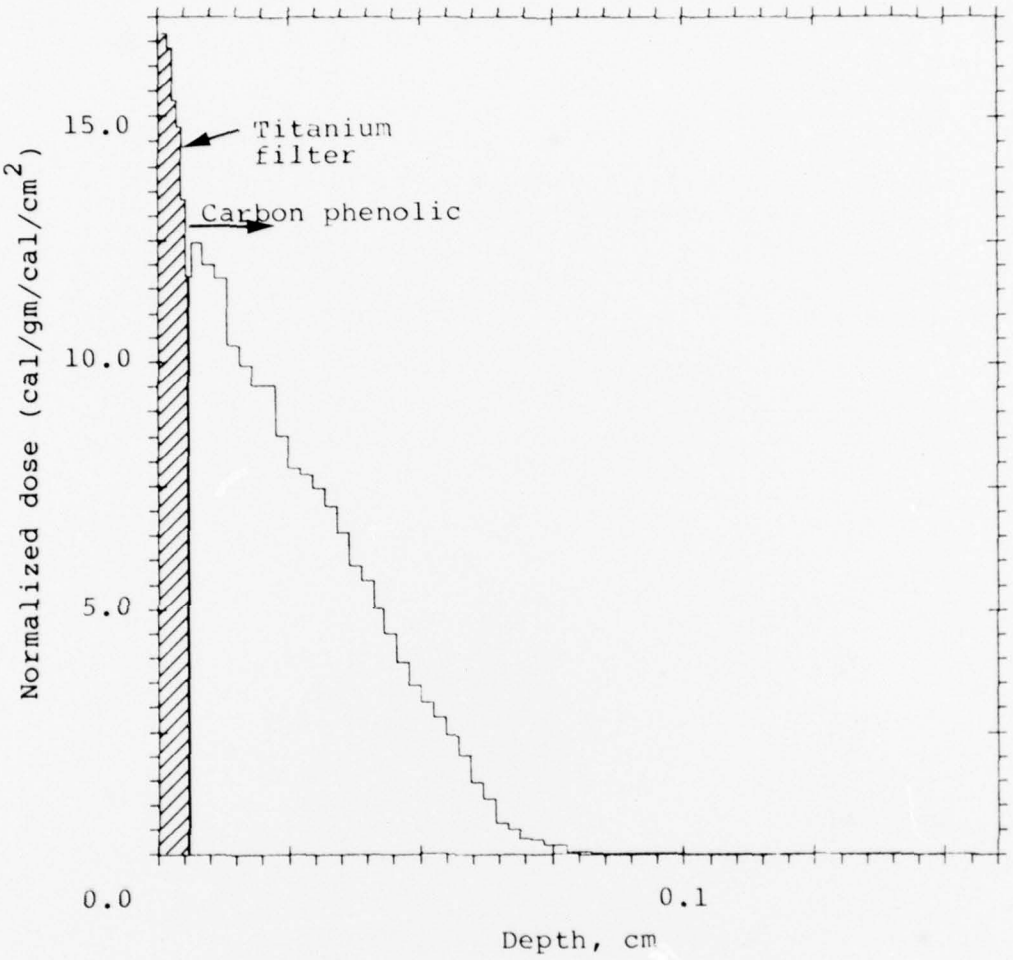

Shot Number 4389
Titanium
filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
10.0
5.0
0.0
0.1
Depth, cm


Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
10.0
5.0
0.0
0.1
Depth (cm)


Shot Number 4394
15.0
10.0
5.0
0.0
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
0.1
Depth, cm


Shot Number 4395
15.0
10.0
5.0
Titanium filter
Carbon phenolic
Normalized dose (cal/gm/cal/cm^2)
0.0
0.1
Depth, cm

Shot Number 4396



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